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Comparison of fatigue constraints in optimal design of jacket structures for offshore wind turbines

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Book of Abstracts

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1 Development of BIW Topologic Optimization Method for Automotive Idling Vibration

Haitao Du

The noise and vibration performance of automotives is critical for overall customer comfort. The stationary vehicle with engine running idle is a very common operating condition in city driving. The acceleration value of steering wheel and seat is considered to be one of the important criteria in customer comfort assessment at the idle condition. It is an efficient method for improve the idle performance that is BIW (Body-in-white) optimization except the powertrain forces optimization. However existing optimized ways and artificial attempt are restricted to specify the weak area quickly and generate new reinforcement structure. In this paper, topology optimization is first applied to find the structural weakness of the BIW (Body-In-White) and new structures are added to improve the overall performance of steering wheel and seat vibration. Only lattice elements are used in the topology optimization method. The key point of new method is to connect the lattice elements to a BIW model made of shell elements and Beta optimization method is used. To demonstrate the benefits, seat vibration optimizations were carried out for full vehicle model. The results show that the newly-developed topology optimization method is valuable in the optimization of automotive components

2 Comparison of different formulations of a front hood free sizing optimization problem using the ESL-method

Artem Karev, Lothar Harzheim, Rainer Immel, Matthias Erzgraeber

Topology and free sizing optimization are very important tools in the designing phase to compute optimized design proposals. However, they are only well established for optimization problems based on linear analysis. In contrast, in the nonlinear analysis area in particular for crash analysis - such kind of optimization cannot be applied due to the unavailability of gradients. A workaround is to create linear auxiliary load cases, which approximate the nonlinear load case at different time steps and which can then be used in optimization based on linear statics analysis. The ESL (Equivalent Static Load) method provides a procedure to create such auxiliary load cases in a well-defined way. A general drawback of such an approach is that responses in the nonlinear system and the related requirements are not defined in the linear statics system. Hence, a formulation must be derived translating the nonlinear requirements in the linear statics system. This is sometimes very difficult and thats why very often the strain energy is used as objective function even if this doesnt reflect the real objective in the optimization task.

In this study different formulations for a front hood free sizing optimization problem are investigated to answer the question how far it is possible to formulate the real objective in the nonlinear system the minimizing of the score in the linear statics system. It turns out that such formulations can be found but that it has no advantage in comparison to simpler formulations. The best performance can be obtained by using the mass as objective function whereas the strain energy formulation fails due to the tendency to favor huge mesh deformations in void areas. The reason for such behavior and the related issues appearing especially in topology and free sizing optimization are explained and discussed in detail.

Finally, some recommendations are given how the performance of ESL-based topology and free sizing optimization could be improved.

5 Investigation of contact settings on the result of topology optimization to avoid contact stiffness supports

Daniel Billenstein, Christian Glenk, Pascal Diwisch, Frank Rieg

Considering adjacent parts in the finite element analysis FEA results in a contact problem. There are several necessary configuration parameters in computational contact mechanics, like the contact stiffness or discretization. Due to this variety there is a multitude of papers regarding the correct range for contact parameters in terms of FEA. In topology optimization especially if the optimization target is set to maximal stiffness the configuration of the contact problem is much more sophisticated. An overlarge contact stiffness for example leads to so called contact stiffness supports. This behavior results in a design proposal, which causes major load flow through the contact zone, whereas the rest of the component is removed. The most difficult part in determining the appropriate range for configuration parameters is comparing different simulations. In topology optimization, it is not sufficient to compare certain stress or displacement values of selected degrees of freedom like it is common in structural mechanic simulations. Instead it is necessary to collate the topology of the resulting design proposals. For this purpose an evaluation algorithm was designed, which supersedes the necessity of a visual evaluation by describing the similarity of two design proposals by means of a histogram. The result of a simulation with the identical design space but with a conforming mesh - thus without contact zone - is used as reference for this computer-aided evaluation. This automated investigation of arbitrary contact configurations shows, that the values of the parameters are within the standard values (recommended in literature), but in a notably smaller interval. In general, smaller contact stiffness is required and the examined parameters are more sensitive in topology optimization. The valid intervals for configuration parameters, which were determined by this method, enable a more realistic way of considering the elastic environment in stiffness optimization.

6 Design of an internally cooled turning tool based on topology optimization and CFD simulation

Tianjian Li

Cutting fluid is traditionally used to remove the generated heat during the metal cutting process. Employing cutting fluid outside the cutting tools may result in environmental pollution, health hazards, and other significant negative consequences. Internally cooled cutting tools are thus desirable and promising for the machining industry. In this paper, an internally cooled turning tool is designed based on topology optimization and CFD simulation, followed by solid isotropic material with penalization (SIMP) model imported in mechanical and heat conduction analyzing models for the tool flow channel design and optimization. The mechanical and thermal results are utilized on a traditional tool to formulate a sound topology optimization model of the internally cooled tool. In comparison with the performance of the traditional tool, the newly designed one can greatly reduce the heat as well as the maximum temperature with minimum deformation. Key performance of the newly configured speed, maximum cooling capacity and maximum tool temperature, are simulated under different flow speeds by fluid-structure interaction thermal analysis.

7 Optimal estimation of tidal flow based on Kalman filter FEM using time history of water elevation

Takahiko Kurahashi, Taichi Yoshiara, Yasuhide Kobayashi, Noboru Yamada

The shallow water flow analysis is frequently carried out to investigate the flow field in shallow water region. In general, the computational results of the shallow water field is obtained by giving data of the water depth and boundary conditions, and so on. However, it is not usual that the computational velocity and water elevation is corresponding to the observed value. Therefore, numerical simulations based on Kalman filter, i.e., one of the data assimilation approach, is applied to estimate the flow field distribution considering the observed value. The shallow water flow analysis based on the Kalman filter FEM has been carried out, and it has been reported that though the computed value at the observation point can be obtained by the observed value, it is necessary to give the boundary condition, even if the Kalman filter FEM is employed. Hence, in this study, the shallow water flow estimation analysis based on the Kalman filter FEM is applied to practical problem considering the result of the previous report. In recent years, performance of some power generation system on offshore, e.g., tidal stream power generation, power generation using tidal change and so on, has been focused since the Great East Japan Earthquake of March 11, 2011. We focused on the tidal stream power generation system as one of the power generation system. In this power generation system, the generated power isn't so big, but, for instance, there is the case that it isn't necessary to get big power, e.g., the power for security right, and security system on offshore and so on. In addition, it is necessary to do the prediction of the generation power before the construction of the tidal stream power generation system. Therefore, in this study, the generation power is predicted based on the result of shallow water flow analysis based on the Kalman FEM in Tokyo bay model.

8 Topological Optimization of Truss Base on Truss-Like Continuum

Kemin Zhou

Ground-structures was a fundamental method to optimize the topology of truss. In ground structures, a great number of members were arranged to link a great number of nodes distributed in design domain. After most of members were deleted by various optimization method, the optimal topology of trusses were found. Generally the members in ground structures were arranged as many as possible, so that the better toppology would be found. However too many members will increase the computation cost. In this paper we suggestted a method to arrange less members in ground-structures reasonably, the cost of computation will decrease greatly. Generally, topological optimum structures are truss-like continuum. In optimal truss-like continuum, the optimal position and orientation of member were revealed. By finite element method, the optimal truss-like continuum can be established already. Therefore, in this paper, the ground structure were established based on optimal truss-like continuum. According the optimal truss-like continuum, the only small numbers of nodes and members in ground structures need be arranged. Only shape optimization and size optimzation were needed in the floowing optimizaiton procedure. Several numerical examples showed that the ground structures from optimal truss-like continuum was very similar to the final optimal solution.

9 Spline-based design optimization of fir-tree root in turbine structures

Ming Li, Fengwei Li, Deqi Yu

To perform optimization and find an optimal configuration of the fir-tree root in turbine structures, how to reasonably characterize the root configuration is a key issue. In the existing researches, the fir-tree root is described with straight lines, arc or even elliptic curves, and the related feature parameters are defined as design variables in optimization. However, this feature-based characterization technique has several drawbacks. This technique yields optimal designs restricted by the defined features assumption, it is difficult to answer why these features are chosen and whether a better feature assumption exists. Moreover, the continuity of the adjoint features hampers the optimization in a large scope. In this study, we characterize the fir-tree root by using a Cubic B-Spline curves through several control points. The horizontal coordinates of these points are defined as design variables, while the corresponding vertical coordinates are fixed. The objective function is to minimize the peak stress in root as objective function. With geometrical, stress constraints, the optimal fir-tree root configuration is obtained corresponding to a better stress distributions and a low stress concentrations. The proposed spline-based optimization approach sheds lights on the conceptual design of root and can be easily extended to other industrial equipment design.

11 Mathematical Models and Methods of Efficient Estimation in Multi-Objective Optimization Problems under Uncertainties

Kateryna Ugryumova, Sergey Chernysh, Ievgen Meniailov, Mykhaylo Ugryumov

The statement of the estimation problem for decision selection criteria (objective functions) and sought values in multi-objective decision making problems under a priori uncertain data is considered. In accordance to the Law of Requisite Variety by W. Ross Ashby, A.N. Kolmogorov's concept of power averages and ideas of regularization methods by A.N. Tikhonov the advanced method of synthesis of decision selection criteria scalar convolutions in multi-objective decision making problems under a priori uncertain data is offered. According to maximum likelihood principle the types of decision selection criteria scalar convolutions are obtained for the multi-objective problems the development of robust meta-models, mathematical models identification and robust design optimization. The types of scalar convolutions of decision selection criteria have been obtained using the Student's statistics as criterion for testing the hypothesis of equality of distribution centers for representative samples of two multidimensional general populations t, and the multidimensional analogue of V.I. Romanovsky criterion for testing the hypothesis of equality of covariance matrices Ro or statistics H instead of statistics Ro, where H is the mutual information.

The mathematical formulations and computational methods, based on the use of the regularizing algorithm, for the synthesis of quasi-solutions of stochastic optimization problems with mixed conditions, has been developed. The application of proposed developments will provide the stable estimates of unknown quantities with a priori uncertain data.

The efficient memetic algorithm with the consistent application of advanced real coded evolutionary method, decremental neighborhoods method, randomized path relinking method of these problems solutions synthesis is proposed. Application of the proposed memetic algorithm provides a reduction of the computing time expenditures for the solution of real-life problems at several times.

12 Shape Optimization of Fully Stressed Design and Channel Flow Problems by Explicit Boundary Tracking

Mingdong Zhou, Haojie Lian, Niels Aage, Ole Sigmund

Performing shape optimization with explicit geometries has been an endeavor for long, but it is usually impeded from the high expense of re-meshing. The development of Deformable Simplicial Complex (DSC) blazes a trail for such goal because of its flexibility in handling large shape deformation through efficient local mesh alterations.

The present works consider two separate shape optimization problems using the DSC method, the fully stressed design and the channel flow design. Both of the problems are benefit from explicit shape update and accurate finite element analysis using a conformal structural mesh of high-order elements, which are essential in obtaining meaningful optimized results as well as revealing the physical insights underneath. For stressed based shape optimization, driving the designable boundaries towards a fully stressed state cannot guarantee an optimal design if the problem is geometrically restricted [2]. For Navier-Stokes flow problems, a new regularization scheme is necessary to suppress the sharp features during the channel optimization as well as to ensure smooth converged geometries [3].

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13 Optimization of finite element mesh division considering stress singularity in bonded structures

Kengo Yamagiwa, Takahiko Kurahashi

In this study, we present optimization of finite element mesh division considering stress singularity for bonded structures. If tensile and bending loadings are applied to the bonded structure, singular stress field occurs around singular point, i.e., interface edge of bonded structure. It is known that stress and strain distribution are expressed by the function of distance from the singular point. In addition, in case of the stress analysis based on the FEM, the value of the stress component at singular point increases with decreasing mesh size around singular point. Therefore, fracture of the bonded structure evaluates by the intensity of stress singularity obtained by the stress distribution. In this study, we propose the optimal mesh division technique for the evaluation of the intensity of stress singularity.

14 Robust Truss Topology Optimization under Uncertain Loads by Using Penalty Concave-Convex Procedure

Yoshihiro Kanno

This paper presents a new formulation of robust truss topology optimization considering uncertainty in the external load. An efficient heuristic method for solving this formulation is also proposed.

A semidefinite programming (SDP) formulation due to Ben-Tal and Nemirovski [A. Ben-Tal, A. Nemirovski, SIAM J. Optim., Vol. 7, pp. 991-1016 (1997)] is well known for robust truss topology optimization. In this approach, it is required to specify the set of existing nodes, to which uncertain loads are supposed to be applied. Then the worst-case compliance is minimized by solving an SDP problem. However, it is difficult to predict in advance the set of nodes that the robust truss design has. This drawback can be resolved by introducing binary variables that indicate existing members in a solution. However, with the binary variables, we can solve only very small-size problems.

In this paper, the robust truss topology optimization is formulated as an SDP with complementarity constraints. This problem is then converted to a form of the difference-of-convex (DC) programming, in which the difference of two convex functions is minimized over a convex set. A concave-convex procedure, which is known as a heuristic for finding a local optimal solution of a DC programming problem, is then applied. We solve an SDP problem at each iteration of this procedure. Numerical experiments suggest that the proposed approach can solve middle-size problems with moderate computational cost. Although this approach is not guaranteed to converge a global optimal solution, it is observed that the obtained solutions are often reasonable from the mechanical point of view.

15 Three-Dimensional Topology Optimization of a Flexible Multibody System via Moving Morphable Components

Jialiang Sun, Qiang Tian, Haiyan Hu

With the development of flexible multibody dynamics, the optimal design of the flexible multibody systems (MBS) has attracted an ocean of attention. Only planar flexible MBS, however, has been topologically optimized because of the long computation time in the traditional pixel or node point-based optimization framework. In this work, a novel three-dimensional topology optimization methodology for a flexible MBS undergoing both large overall motion and large deformation is proposed. Firstly, the flexible MBS of concern is accurately modeled via the three-dimensional solid brick element of the absolute nodal coordinate formulation (ANCF), which utilizes positions of nodes and slopes as sets of generalized nodal coordinates. Secondly, to deal with the dynamic characteristics in the optimization process, the equivalent static load method is employed to transform the dynamic topology optimization problem into a set of static problems. Last but not least, in order to reduce the computational burden, the newly-developed moving morphable components (MMCs) based topology optimization method is reevaluated to optimize the three-dimensional flexible MBS. The MMCs based framework incorporates more geometrical and mechanical information into the topology optimization directly and can optimize large flexible MBS with high efficiency. Two numerical examples are presented to validate the effectiveness of the proposed optimization methodology.

16 A novel local surrogate assisted global optimization method for high dimensional problem

Fan Ye, Hu Wang

Surrogate models are widely used in simulation-based engineering design and optimization to save the computational cost. In this work, a local surrogate assisted global optimization method is suggested. During the sampling process, the approach uses rectangles to partition the design space and construct local surrogates according to existing sample points. The size of rectangles is adaptively generated by the maximum distance of the centered sample point between other points. The large size of the rectangle indicates that the constructed local surrogate may be low accurate, and the extended size of the rectangles indicates that new sample points should be sampled in this local region. On the other hand, considering the exploration of the design space, an uncertainty predicted by using the Kriging model is integrated with the local surrogate strategy and applied to the global optimization method. Finally, comparative results with several global optimization methods demonstrates that the proposed approach is simple, robust, and efficient.

17 Topological Optimization in Fourier Space

Daniel White, Mark Stowell

Topological optimization of elastic structures has important application in architecture and civil engineering, mechanical and industrial design, micro and nano technology, biomedicince, etc. The most common approach begins with the finite element discretatization of the linear elastic PDE on a uniform Cartesian mesh, and the material volume fraction (which is the optimization decision variable) is represented by piecewise constant values on this mesh. In lay terms, the volume fraction is represented by pixels (2D) or voxels (3D). It is well known that the SIMP method can result in an undesirable checkerboard pattern, and various filters have been developed to mitigate the checkerboarding.
Filtering of volume fraction using a cone filter, Helmholtz filter, or related filters is equivalent to a low-pass filter operating on an image. It is well known that after low-pass filtering, the pixels in an image are correlated, they are no longer independent. This means that there exists a change of basis that will result in a more compact representation of the image. As a starting point for investigating compact representations we begin with the Discrete Cosine Transform (DCT). In our approach, the 3D volume fraction is represented by a 3D inverse DCT, and the optimization decision variables are the coefficients of the transform. Hence, the elastic PDE is solved in physical space, but the optimization is performed in Fourier space. There are several advantages to this formulation. First, no additional filtering step is required. The minimal feature size is controlled by specifying the number of Fourier coefficients. Second,

the number of decision variables can be reduced significantly. A third advantage is that the decision variables are decoupled from the finite element discretization, hence the finite element mesh can be highly refined, even adaptively, without adversely affecting the optimization.

19 Topology optimization of freely vibrating continuum structures based on nonsmooth optimization

Pingzhang Zhou, Jianbin Du, Zhenhua Lv

The non-differentiability of repeated eigenvalues is one of the key difficulties to obtain the optimal solution in the topology optimization of freely vibrating continuum structures. In this paper, the bundle method, which is a very promising one in the nonsmooth optimization algorithm family, is proposed and implemented to solve the problem of eigenfrequency optimization of continuum. The bundle method is well-known in the mathematical programming community, but has never been used to solve the problems of topology optimization of continuum structures with respect to simple or multiple eigenfrequencies. The advantage of this method is that the specified information of iteration history may be collected and utilized in a very efficient manner to ensure that the next stability center is closer to the optimal solution, so as to avoid the numerical oscillation in the iteration history. Moreover, in the present method, both the simple and multiple eigenfrequencies can be managed within a unified computational scheme. Several numerical examples are tested to validate the proposed method. Comparisons with nonlinear semidefinite programming method and 0-1 formulation based heuristic method show the advantages of the proposed method. It is showed that, the method can deal with the nonsmoothness of the repeated eigenvalues in topology optimization in a very effective and efficient manner without evaluating the multiplicity of the eigenvalues.

20 Multi-objective Structural Optimization and Design of Microsatellite Supporting Legs

Hao Xu, Yong Zhao, Wen Yao, Ning Wang, BingXiao Du

Abstract: The supporting legs of TianTuo-3 microsatellite support the satellite and can protect the antennas and other devices, but original design relies on experience of engineers and experiment. The design period is long and the cost is expensive, and structure is always conservative. Optimization Driven Design Process (ODDP) is applied and a multi-step optimization strategy which is more efficient is proposed to find a better design of the supporting legs in TianTuo-3 Microsatellite. First, an optimal topology configuration of leg is obtained by utilizing Solid Isotropic Material Penalty (SIMP) approach, considering minimization of compliance. Then, a multi-objective shape and size optimization is built considering strength, stiffness and stability requirements based on Non-dominated Sorting Genetic Algorithm-II (NSGA-II). Finally, after several rounds of design iteration by engineer, a brand new design is given. The mass of one leg, axial fundamental frequency and max von Mises stress are decreased by 17.93%, 4.52% and 11.67% respectively compared with original design. Buckling factor and lateral fundamental frequency are increased by 74.24% and 6.52% respectively. It shows that the multi-step strategy has obviously advantages than traditional design process.

23 The multi-constraint and multi-objective optimization of crane

Kunming Zheng, Youmin Hu, Bo Wu, Tielin Shi

In order to save energy, convenient for transportation and improve the crane's operation efficiency, the crane component is toward lightweight. How to improve the running speed and load capacity on the premise of lightweight of the component, and reduce the vibration and position error of the crane system is relate to the optimization problem with multi-constraint and multi-objective. For the high speed and lightweight crane, except for the speed, precision, stiffness and other performance indicators, which are based on the kinematics model and rigid body dynamics model, on elastic dynamics level, high speed causes the rise of inertia force excitation frequency, lightweight causes the component flexibility and decreases the system natural frequency, the elastic dynamics factors can lead to the elastic vibration and position error, and have great effect on the working performance of the crane seriously. The specific optimization research methods to be adopted as follows: establishing the mechanism error model and elastic dynamics model of the crane, and the kinematics, rigid body dynamics, elastic dynamics and vibration characteristics are considered comprehensively, taking the mean position of end-effector and mean fundamental frequency of crane system as the optimization objective functions, and the installation scale, speed, precision, stiffness and rigid body dynamic performance are regard as constraint condition, through making appropriate optimization algorithm, the optimized scale parameters of main components can be obtained. Finally, in order to verify the correctness of this paper's method, the optimized model of the crane is built, and the vibration characteristic and position error are analyze in dynamics simulation software, the results shown that the operating efficiency and working speed are improved, and the system vibration and position error are reduced.

24 Modifications of Bi-directional Evolutionary Structural Optimization for Structure Compliance

Vu Truong Vu

Bi-directional evolutionary structural optimization (BESO), an updated version of evolutionary structural optimization (ESO) (Xie and Steven, 1993), is a simple and fast method for certain topology optimization problems. The key feature in ESO/BESO is evolutionary rate which determines the speed of evolution. To the author's best knowledge, past studies set the evolutionary rate as a prescribed constant and once the evolution starts there is no concern about its effect on the evolution process. The paper mainly presents a modification of the evolutionary rate in BESO for structural compliance minimization.

In the approach, a self-adapting evolutionary rate based on variation of the structure compliances is proposed. It means the volume change in each iteration will be adjusted to balance its effect on the objective function. Additionally, golden section search is used in averaging the sensitivity of compliance instead of bi-section search in the 'soft-kill' BESO (Huang and Xie, 2010). Furthermore, initial evolutionary rate, filter radius and penalty exponent in material model are tuned to get the appropriate values. The proposed simple technique improves results of benchmark problems in the literature.

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25 Optimization of 3D bifurcation stability

Pauli Pedersen, Niels Leergaard Pedersen

For a continuum with load distribution and specified support conditions, a bifurcation load factor may be estimated by solution of an eigenvalue problem. The necessary data for this eigenvalue problem are obtained by solution of a static equilibrium that for accuracy of the bifurcation load factor must be solved as a case of non-linear elasticity. From this, localized analytical sensitivity of 3D continuum bifurcation load factor is obtained, with direct physical interpretation of the involved factors.

The eigenvalue problem include the tangent stiffness matrix separated in the stress stiffness matrix and the remaining part. Element analytical expressions for these matrices are available and especially the stress stiffness matrix is simple. Two aspects of the eigenvalue problem simplify the sensitivity analysis, defined as change in load factor as a function of a specific element design parameter. At first, the gradient of the Rayleigh quotient is stationary with respect to the eigenmode, i.e. the change in bifurcation mode will not influence the first order derivative. Secondly, the accumulation from element energies, with only local explicit influence from design parameter to the element matrices, imply that local analytical sensitivity analysis can be applied.

The eigenvalue problem is solved by the method of subspace iteration giving the eigenvalues and the corresponding bifurcation modes. For a mode the Rayleigh quotient is equal to the eigenvalue stated in energy terms, that may be directly accumulated from element energies, noting that the element stress stiffness matrices are indefinite. Implemented in a finite element approach the inherent complexity of mode switching and multiple eigenvalues is found not to be a practical problem. The number of necessary redesigns is of the order 10-20 as illustrated by examples, where also different cases of stiffness interpolation and of total amount of available material for a design space are exemplified.

26 Optimization of bolted flanges

Niels Leergaard Pedersen

The tower of wind turbines are typically today designed as circular tubes, and the different sections are assembled by a bolted flange joint. Due to production and transportation constraints the usual used design is a L-flange that is known to give an eccentric loading on the bolt. This gives rise to a non-linear relationship between external tower load and the bolt tensile load in the preloaded bolt. In design standards and in papers different models for the non-linear response are given but large variations exist. The present work focus on two aspects; finding a simplified expression for the non-linear force response based on finite element calculations that includes contact analysis, and secondly focus is on optimization of the flange design which is shown to considerably improve the strength of the connection. The strength of the flanges are controlled by fatigue, so stress amplitude is the primary objective.

The overall inherent shortcomings of the L-flange can be improved in quite many ways. The present work focuses on moderate design modifications of the original simple design for improving the strength in order for the results to be practically applicable. Different design modifications are investigated in the work, these include; adding stiffeners, adding a neck or specific design modification of the contact surface area. These types of design modification are found to be only beneficial for a relatively small range of the external loadings and only for the case of designing the contact area. In the case of stiffeners these will in themselves improve the design, however in order to fulfill the requirements with respect to spacing around the bolt head the number of bolts have to be reduced leading to an overall weaker design. The added neck fails because the loading condition is bending of the tower wall. It is however found that improvements of up to 65% can be found by changing the flange dimensions and the positioning of the bolt in the flange.

27 Topology Optimization for the Design of Conformal Cooling System in Thin-wall Injection Molding Based on BEM

Zheng Li

A topology optimization approach for designing the conformal cooling system for injection molding is developed in this paper. During this process, the cycle-averaged approach is used to simplify the analysis of cooling process, and the boundary element method (BEM) is adopted to solve the governing equations and calculate the sensitivities. The optimization starts with a complex network of channels, and the radius of each channel section as well as the location of each node are selected as the design variables. The topology of the cooling system can be modified by deleting excessively thin channel sections. We pick out two representative example models with areas that are hard to cool to test the effectiveness of the developed optimization approach. The results show that our method can improve both efficiency and uniformity of the cooling process.

29 Volume-constrained expected compliance minimization in continuous topology optimization with normally distributed and correlated random load directions

Anikó Csébfalvi, János Lógó

Uncertainty is an important consideration in topology optimization to produce robust and reliable solutions. In this paper, we assume that the only source of uncertainty is the variability of the applied load directions. The most models in this area apply parametric statistical tools to describe the directional uncertainty of the loads assuming that the uncertain directions are normally distributed statistically independent (uncorrelated) random variables. In this paper we present a new algorithm for the volume-constrained expected compliance minimization with normally distributed and correlated random loading directions using numerically generated objective and gradient function values. The algorithm is a straightforward extension of the algorithm that was described in [1] for the uncorrelated case. This algorithm is based upon the finding that for a particular set of statistical parameters the integration in the expected compliance function can be done symbolically using symbolic manipulation software. The symbolically generated exact expected compliance function will be a simple linear function defined on a particular subset of the inverse stiffness entries which is needed in the compliance computation. For the numerical treatment of the problem the standard optimality criteria (OC) method was used with exact analytical sensitivities. Unfortunately, in the correlated case, the symbolic manipulation softwares are unable to cope with the symbolic integration problem without strong simplifications; therefore we had to replace the exact analytical objective and gradient evaluations with their accurate numerical approximations in the optimal solution searching process. The essence and viability of the proposed approach will be demonstrated by the detailed description of a 2D cantilever beam problem with two loads with normally distributed and correlated random load directions.

30 A multi-grid reanalysis solver for expensive computational optimization

Hu Wang, Zhenxing Chen

The purpose of this study is to use reanalysis method instead of the surrogate model expensive computational optimization. Under such framework, the efficiency of optimization can be significantly improved. Compared with other reanalysis methods, the distinctive characteristic of the multi-grid reanalysis(MGR) method is that the consistency between the modified and the initial meshes is not required. A modified mesh without any consistency with the initial mesh can be well solved by this way, even if it is totally re-meshed after modification. Therefore, the difficulty of mapping between the initial and modified structures can be avoid. Compared with the Surrogate Assisted Optimization (SAO), the advantage of reanalysis is that the error can be well controlled, thus the accuracy of optimization should be improved significantly. Two numerical examples are used to verify the performance of the proposed method.

32 Sensitivity analysis through constrained variational principle and its application in optimization of thermal actuator

Qi Xia, Tielin Shi

In the structural topology optimization, the objective and constraints characterizing a structures performance are functions of the state variables that are the solutions to one or more partial differential equations (PDEs) governing the behavior of structure. The Dirichlet boundary condition in the PDE is usually implicitly accounted in the weak form equation through the space of admissible functions. However, this is not convenient for the sensitivity analysis of the Dirichlet boundary. In the present study, the constrained variational principle is employed to explicitly include the Dirichlet boundary condition into the weak form of PDE.

Thermal actuator uses thermal expansion of an elastic body to produce motion at its output port. In order to deliver an output displacement that is large enough, thermal actuator should have a proper geometry such that small local thermal expansion at each material point can be accumulated and amplified, since the thermal expansion coefficient of solid material is generally small. In addition, in order to ensure the output displacement is along a required direction, thermal actuator should have a proper support to constrain expansion in irrelevant directions and to steer it to the direction of interest, since in most cases the thermal expansion is isotropic.

Topology optimization of thermal actuator and its support is essentially the simultaneous topology optimization of two different types of boundaries: the free boundary and the Dirichlet boundary. As compared to conventional topology optimization of a single type of boundary, the optimization of multiple types of boundaries has much greater potential to produce more significant enhancement of performance. In order to solve the optimization problem of the present study, a level set based multiple-type boundary method proposed in our previous study is employed.

33 Shape and structural design optimization of graphene sheets in natural vibration problem

Jin-Xing Shi, Keiichiro Ohmura, Masatoshi Shimoda

Because of their superior mechanical, structural, and electronic properties, graphene sheets (GSs) are supposed to be components of nanoelectromechanical systems (NEMS). In this study, we carry out shape and structural optimization of GSs with topological defects in natural vibration problem to enhance their fundamental frequencies. At first, we model GSs as continuum shells based on the molecular mechanics method. Then, we carry out shape design optimization of GSs by using a developed free-form optimization method for shells. In the shape design optimization, we use the fundamental frequency as objective function and enhance it considering volume constraint and repeated eigenvalues. Next, we derive the optimal atom structures of GSs with topological defects using a combination of Phase-Field-Crystal method, Voronoi tessellation method, and molecular dynamics method. The numerical results show that the fundamental frequencies of GSs can be significantly enhanced according to the shape and structural design optimization, and we can get their optimal atom structures with defects, which is helpful for designing GSs components in NEMS.

34 Force density method for simultaneous optimization of geometry and topology of trusses

Makoto Ohsaki, Kazuki Hayashi

Topology optimization of trusses is a well-established field of research, and various methods including mathematical programming and heuristic approaches have been developed. The ground structure approach is generally used for obtaining a sparse truss from a highly connected ground structure. In this process, the nodal locations are fixed; therefore, a dense ground structure is needed to obtain appropriate locations of nodes.

Optimization of nodal locations of trusses is called geometry optimization or configuration optimization. This process is rather easy, if the possible location of each node is restricted in a small neighborhood region of the initial location. When optimizing the geometry of a truss, the member cross-sectional areas are also preferred to be varied, and the thin members after optimization are to be removed. However, if the nodes are allowed to move in a wide range of the design space, then so-called melting nodes will exist, where closely spaced nodes are connected by very short members.

In this study, a new method of simultaneous optimization of geometry and topology is presented for plane and spatial trusses. Compliance under single loading condition is minimized for specified structural volume. The difficulties due to existence of melting nodes are successfully avoided by considering force density, which is the ratio of axial force to the member length, as design variable. The nodal locations as well as the cross-sectional areas are regarded as functions of force densities. After obtaining optimal cross-sectional area, nodal locations, and topology, the cross-sectional areas and nodal coordinates are further optimized using a conventional method of nonlinear programming. Accuracy of the optimal solution is verified through examples of plane trusses and a spatial truss. It is shown that various nearly optimal solutions can be found using the proposed method.

35 On penalization strategies for failure indices in Discrete Material and Thickness Optimization problems

Erik Lund

For design optimization of laminated composite structures with varying thickness the Discrete Material and Thickness Optimization (DMTO) approach has proven to be an effective gradient based method for mass minimization problems with constraints on global criteria like compliance, eigenfrequencies, and buckling load factors. The DMTO approach is an extension of the DMO approach where the discrete problem of selecting the best candidate among a number of candidate materials is converted to a continuous problem using interpolation functions with penalization. In the DMTO approach the DMO material interpolation schemes are extended by including a topology (density) variable so to effectively terminate individual plies throughout the laminate.
The use of density approaches for stress constraints in standard topology optimization with isotropic materials is now relatively well-established using the qp-approach by Bruggi combined with aggregation functions in order to reduce the potential very large number of stress constraints. This work is based on an extension of such approaches when including failure indices in the optimization problem. For laminated composite structures the failure indices used for predicting failure must be evaluated layerwise, resulting in very many failure indices to consider together with the problem of having very many design variables. The candidate materials can be different fiber reinforced polymers (CFRP/GFRP) oriented at different fiber angles together with foam materials, and different strain or stress based failure indices are typically applied for the different candidate materials. The behavior of the resulting interpolation between these failure criteria depends on the interpolation schemes used and the penalization strategies applied, which will be documented on a number of benchmark examples. The work will also present the suggested penalization strategy to apply and demonstrate it on a large scale engineering problem.

36 Latest Developments for Industrial Adjoint Sensitivity Analysis and Non-Parametric Optimization

Claus B.W. Pedersen, Kingshuk Bose, Michael Wood, Rong Fan, Vladimir Belsky

The latest developments obtained by integrating adjoint sensitivities into a general non-linear FE-solver will be shown by numerical experiments and applications for topology and non-parametric sizing optimization, respectively. We show for models consisting of small-sliding frictionless contact with linear material behavior and small displacements and rotations that we can solve the structural residual and contact inequality constraints using a so-called "Linear Complementarity Problem" (LCP) technique. The LCP contact technique basically solves the structural equilibrium of all contact load cases as a single linear load case in CPU-time with a diminutive amount of additional overhead in CPU-time as a function of number of contact load cases. A frequent approach is to tie the contacts of the interfaces between the parts often yielding incorrect optimization solutions as the stiffness of the interfaces are modeled having too high stiffness which the optimization algorithm exploits. Secondly, it is demonstrated that realistic simulation including pre-loading of the assemble process, stiffness of the bolt connections and contacts can be included for obtaining realistic additions to the actual service-loads being applied for the optimization to achieve realistic optimization results. Thirdly, optimization using the adjoint sensitivities for design responses of finite element results including material non-linearities, geometrical non-linearities for large deformations and contact as well as of various element types as shell elements and surface stress integrated element types will be shown.

37 Multiscale, thermomechanical topology optimization of cellular structures for porous injection molds

Tong Wu, Doyle Hewitt, Kim Brand, Andres Tovar

During the injection molding cycle, molten material is injected at high pressure inside the mold and cooled down to form a solid part. This creates thermomechanical stresses that are alleviated by the correct design of a cooling system. In conventional molds, the cooling system consists of straight-line cooling channels, which can be manufactured using machining processes; however, they are thermally inefficient and unable to cool the injected part uniformly. The emergence of metal-based additive manufacturing techniques such as direct metal laser sintering (DMLS) allows the fabrication of molds with conformal cooling channels. Conformal cooling molds cool down the part faster and more uniformly; however, they face limitations. First, their fabrication cost is 10 to 20 times higher than the one of a conventional mold. Second, the DMLS process, which is the most popular fabrication method of conformal cooling molds, produces internal thermal stresses that distort the mold. The development of structural optimization methods such as multiscale topology optimization offers the potential to create novel and complex cellular structures that alleviate these current limitations. The objective of this research is to establish a multiscale topology optimization method for the optimal design of non-periodic cellular structures subjected to thermomechanical loads. The result is a hierarchically complex design that is thermally efficient, mechanically stable, and suitable for additive manufacturing. The proposed method seeks to minimize the mold mass at the macroscale, while satisfying the thermomechanical constraints at the mesoscale. The thermomechanical properties of the mesoscale cellular unit cells are estimated using homogenization theory. A gradient-based optimization algorithm is used for which macroscale and mesoscale sensitivity coefficients are derived. The design and evaluation of a porous injection mold is presented to demonstrate the proposed optimization method.

38 Metamodel-based global optimization of vehicle structures for crashworthiness supported by clustering methods

Kai Liu, Duane Detwiler, Andres Tovar

This work introduces a metamodel-based global optimization method for crashworthiness with the ability to synthesize continuum structures with an optimal distribution of material phases and thin-walled structures with an optimal distribution of gauges. The proposed optimization method makes use of fully nonlinear, dynamic crash simulations and consists of four main elements: (1) the generation of a conceptual design from the structure's crash response, (2) the optimal clustering of the conceptual design to define the location of the material phases or gauges, (3) the optimal definition of metamodels, and (4) the global optimization, which aims to find the optimal settings for each cluster. The conceptual design is a continuous distribution of the design variable (material phase or gauge) as a function of the structure's response to the crash event. Such response may include internal energy density or other strain/stress functional. For instance, this work illustrates the use of mutual potential energy for progressively folding thin-walled structures. The optimal clustering of the conceptual design is a key element of the method since it reduces the dimensionality of the problem to a tractable number of design variables. In the clustered structure, each cluster contains three variables: lower bound, upper bound, and the design variable value. These values are optimized to define the optimal clustering. From the clustered design, metamodels are created using a Latin hypercube sampling. Then, they are sequentially enhanced using an expected improvement function. Finally, global optimization is performed using a multiobjective genetic algorithm (MOGA). The proposed methodology is demonstrated in continuous and thin-wall vehicle structures undergoing crash (frontal/axial and side impact). The results are compared with existing structural design methods for crashworthiness including the hybrid cellular automaton (HCA) method incorporated LS-TaSC (LSTC, California).

39 Structural robust topology optimization under uncertain dynamic loads

Xiaopeng Zhang, Zhan Kang, Akihiro Takezawa

This paper investigates the structural topology optimization method of structures subjected to uncertain harmonic excitations or ground accelerations. The excitation uncertainty is described with an ellipsoidal convex model. A nested double-loop problem is first formulated for the robust topology optimization. Since the dynamic compliance may become negative when the external excitation frequency is higher than the structural fundamental frequency, the absolute dynamic compliance is taken as the objective function. We then propose a method to seek the worst-case objective function value directly by evaluating the maximum/minimum eigenvalues and the corresponding eigenvectors of an inhomogeneous eigenvalue problem. Here, a generalized compliance matrix is introduced as a mapping of the structural dynamic compliance matrix to the load uncertainty space. The outer-loop optimization problem is solved by a gradient-based mathematical programming method. To this end, the sensitivity analysis of the worst-case objective function value is derived with the adjoint variable method. The sensitivity analysis of the worst-case objective function value, and then the optimization problem is solved by sensitivity-based mathematical programming method. Numerical examples are presented to illustrate the effectiveness and efficiency of the proposed framework.

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41 Integrated topology optimization of multi-component system considering interface behavior of interconnection based on conforming mesh and interface elements

Pai Liu, Zhan Kang

Integrated topology optimization of multi-component system refers to simultaneous optimization of the layouts of the components and the topology of the host structure supporting these components. In the present study, we propose a method to account for the behavior of the connecting interface between the components and the host material. Here we treat the connecting interface with the cohesive zone model. A conforming mesh in conjunction with the interface elements are employed to discretize the evolving structure while accounting for the strong discontinuity of displacement field across the interface. To give clear representation of structural boundaries and the connecting interface, we also use a multi-material interpolation model in the level set framework. An objective function that contains the work dissipated by the traction on the connecting interface is considered and the evolution velocities of the level set functions are treated as design variables. The sensitivities are derived with the adjoint method and the design variables are obtained with the MMA optimizer. The MMA optimizer makes it easier to handle multiple constraints in level set based optimization problem. The design is updated via the Hamilton-Jacobi equation with the velocity design variables as input. Re-initialization is employed to preserve the signed distance property of the level set functions. Two numerical examples are shown to illustrate the validity and applicability of the proposed method.

42 Confidence-Based Uncertainty Quantification and Reliability Assessment with Limited Number of Input and Output Test Data

KK Choi, Hyunkyoo Cho, Min-yeong Moon, Nicholas Gaul

A simulation-based method can be used for accurate uncertainty quantification (UQ) and prediction of reliability of the physical system provided: (1) accurate input distribution models and (2) accurate simulation model are used. However, in practical engineering applications, only a limited number of input test data is available for modeling input distributions. Also the simulation model needs to be validated using only a limited number of output test data that is available. In this paper, computational methods and a process are developed to obtain confidence-based UQ and reliability assessment for limited numbers of input and output test data, which induce uncertainties in input distribution models and output distributions, respectively. First, uncertainties of input distribution models induced by insufficient input test data are obtained. Due to these uncertainties, there are many corresponding output

PDFs obtained using the biased simulation model. Second, uncertainty of the target output distribution is obtained using the insufficient output test data and biased simulation output PDFs obtained. To obtain uncertainty distribution of the reliability, a hierarchical Bayesian model is used. Once the uncertainty distribution of the reliability is identified, we can specify a target confidence level. At the target confidence level, the confidence-based target output PDF and reliability are selected, which are confidence-based estimations of the true output PDF and reliability. Using the confidence-based target output PDF and reliability, a model validation optimization is carried out for correction of the model bias. In this optimization, the distance between biased simulation output PDF and confidence-based target output PDF is minimized while satisfying confidence-based reliability. Once we obtain the validated simulation model, confidence-based UQ and reliability of the physical system can be assessed without requiring a large number of input and output test data.

43 Thermal Error Control Technique for Precision Parts of Machine Tools Based on Thermal Deformation Balance Principle

Xiaohong Ding, Zeji Ge, Jiali Gao

Thermal deformation is the key factor to affect the processing precision of machine tools, thus it is important to control the thermal deformation of precision functional parts of machine tools during processing. This paper suggests a thermal deformation control method based on the thermal deformation balance principle, the essential of which is to utilize the heat shrinking material, Carbon Fiber Reinforced Plastic (CFRP), to compensate the thermal expansion of metal structure. The metal structure is bonded with CFRP bandage, and thermoelectric modules (TEMs) are used to achieve the temperature difference between the metal and CFRP in order to realize the same thermal deformation. The mathematic model of deformation balance principle and energy analysis of aluminum-CFRP structure are studied firstly. And two kinds of compensation system for reducing thermal deformation are designed respectively, which are simplified slider and spindle structures. In the compensation system of slider structure, an optimal layout of heat transfer channel is designed by SIMP method to distribute the heat evenly on CFRP bandage. Conductive graphite with ultra-performance of heat conduction makes it possible that the CFRP bandage can be heated uniformly. While in the compensation system of spindle structure, CFRP bar is designed by the sizing optimization method to reduce its material cost. The effectiveness of the suggested method is validated by both experimental and numerical simulation results. The thermal displacement of the slider structure is reduced by 97% , and the axial thermal deformation of spindle housing is reduced by 98%.

46 Topology optimization of composite structures for fracture resistance with phase field modeling of crack propagation

Liang Xia, Daicong Da, Julien Yvonnet

In this paper, we propose a numerical design framework for the fracture resistance improvement of composite structures through an optimal design of the inclusion phase distribution. The phase field method to fracturing with a regularized description of discontinuity is adopted for the modeling of crack initiation and propagation. For a prescribed material volume usage of the inclusion phase, topology optimization using an extended bi-directional evolutionary structural optimization (BESO) method is performed to find an optimal inclusion distribution that maximizes the fracture resistance. A computationally efficient adjoint sensitivity formulation is derived that accounts the whole fracturing process until the structure is fully cracked. A series of 2D and 3D numerical examples are presented.

50 Optimal external support structure design in additive manufacturing

Yu-Hsin Kuo, Chih-Chun Cheng

A series of strategies for designing support structure to fabricate overhanging features in additive manufacturing (AM) is proposed. The focus of this study is to maximize the external support stiffness while requiring supports that can be easily removed, minimizing the time required to add the supports, and using the least amount of material. These design requirements become necessities not only for adding supports to improve processing and post-processing efficiency, but also for reducing the cost of supports while maintaining specimen geometry. A repulsion index (RI) is proposed for satisfying the easy removal requirement and minimizing the size of artifacts left on the specimen surface; a weighting function is applied to quantify the time consumption to build the supports. The proposed RI and cost due to additional material and time consumption in adding the support are formulated within a multi-objective topological optimization constructed by the simple isotropic material with penalization method, continuous approximation of material distribution, and method of moving asymptotes. Numerical simulations demonstrated that rational and cost effective support layouts can be determined by the proposed cost-based formulation. This allows designers to find design solutions with a compromise between the deformation and the cost of support structure.

51 Evolutionary Topology Optimization for Designing Cellular Fluid Actuators

Daniel Cunha, Renato Pavanello

Bio-inspired shape adapting systems, based on plants that can reshape themselves by altering the pressure in their cells, can attain very desirable features, such as light weight, large actuation and simple input. It is proposed to design efficient fluid actuators as cellular compliant mechanisms, in which each cell is internally loaded by pressured fluid cavities, through topology optimization techniques. In this work, a model for such cells was proposed, the finite element analysis, sensitivity analysis and optimization method were described and implemented. The chosen optimization method was the soft-kill Bidirectional Evolutionary Structural Optimization (BESO) method with material penalization. The loads dependency on the topology together with two considered nonlinear effects (geometrical nonlinearity and load nonlinearity) act as hindering factors to the optimization process as a whole. Cells with maximized expansion were obtained for two cases: cells that actuate only horizontally; and cells that actuate both horizontally and vertically.

52 Optimization Method for Creating Minimal Surface Discretized by Parametric Surface

Shinnosuke Fujita, Yoshihiro Kanno, Makoto Ohsaki

The membrane architectural structures are constituted by flexible members which do not resist bending such as film materials and cable materials, and their mechanical stability greatly depends on the shape of the initial surface. In order to design a membrane structure having mechanical stability which does not cause wrinkles or slackness, it is common to adopt an isotonic surface as the initial design surface of the membrane structure.
Some previous studies proposed methods of obtaining a surface with minimal surface area under appropriate subsidiary conditions by utilizing the fact that the isotonic surface is the same as the minimal curved surface.
However, in any of these studies, since the surface is approximated by triangular elements and the sum of the triangular elements area is minimized, the error from the true minimal surface greatly depends on the division method of triangular elements.
If the triangulation is made finer, a minimal surface with higher precision can be obtained, but the computational cost increases and the obtained minimal surface becomes a collection of enormous nodal information. The amount of data becomes enormous and it is difficult to smoothly convert or deliver as 3D graphic data in the situation of using CAD/CAE.
In contrast, if we use a parametric surface, it is possible to explicitly calculate the surface area in parametric expression. Also, the minimal surface is known as a surface in which the average curvature is equal to 0 at any point on the surface. By measuring the average curvature, it is possible to quantitatively evaluate the error from the true minimal surface.
In this research, to create the minimal surface which can explicitly express numerical functions with a small data volume, we solve the optimization problem with the surface area and the average curvature in parametric expression as the objective functions, and the effectiveness of proposed method is discussed.

54 Structural topology optimization of coated structures using level set method

Yaguang Wang, Zhan Kang

The coated structure is composed of the substrate and the coating layer, which is commonly used in engineering. The coating material covers the surface of the substrate for protection or to improve certain functionalities. It can also combine the merits of both the coating and substrate material properties. Recently, the rising of additive manufacture as a new production process enables higher design flexibility for such coated structures. This paper presents a level set-based topology optimization method for the design of structures with coating layers. Though a coated structure is composed of two-phase materials, only one level set function is needed in the special case of coating with uniform thickness to describe the distribution of the substrate and the coating layer, thanks to its signed distance property. The proposed method provides a direct interface description between different material phases and an exact geometrical representation regarding the coating layer thickness, thus facilitating the sensitivity analysis and numerical implementation. Numerical examples show that the method can be applied to both 2D and 3D problems.

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56 Topology optimization of electro-mechanical-acoustic micro devices

Niels Aage, Anders Lilije Møller, Jakob Søndergaard Jensen

Structural optimization methods applied to the design of micro-electro-mechanical systems (MEMS) has been studied with successful outcome for the past two decades. To extend the capabilities of the density based topology optimization methodology, we explore the possibility of designing MEMS devices for specific acoustic pressure properties. Adding acoustics to the already multiphysical problem paves the way to study design problems including transducers, hearing aid receivers/transmitters and other audio based MEMS devices e.g. sensors and mobile phone components.

The proposed methodology is based on a monolithic mechanical-electrical model. The mechanical and electric problems are coupled through the Maxwell stress tensor which in turn depends on the intensity of the electric field, which in return depends on the deformation. To incorporate the acoustic pressure field into the design problem we apply a mixed u-p formulation for the mechanical problem using a stable Q9Q4 2d discretization. As we want to solve the electro-mechanical-acoustic problem in the frequency domain, we first solve for the static state of the mechanical-electrical system. This is followed by a linearization of the dynamic equations about the deformed equilibrium, which is then perturbed by a mechanical, time-harmonic load. We demonstrate the capabilities of the proposed design formulation by solving the following model problem: Based on a mechanical time-harmonic excitation, we seek to find the material distribution consisting of solid/conductor and acoustic media/insulator materials that minimizes (or maximizes) the acoustic response, i.e. the sound pressure pressure level, in a specified region of the modeling domain.

57 Layout optimization of cable-suspended membrane structures for wrinkle-free design

Yangjun Luo, Yanzhuang Niu, Ming Li, Zhan Kang

Cable-suspended membrane structures have been widely used in many large gossamer structures and architectural engineering problems, such as solar sails, sun shields, large-aperture spacecraft antennas, and fabric tension structures. These structures may be tens or even hundreds of meters in size, and characteristically contain a limited boundary cables and large areas of thin membranes. Compared with pure membrane structures that are easily subject to wrinkles under external loads, a cable-suspended membrane design may be more structurally efficient because the boundary cables in tension can make the membrane as uniformly as possible without increasing the structural mass significantly.

Wrinkling is a common phenomenon found in a variety of membrane structures due to the lack of bending and compression stiffness. In order to eliminate stress-related wrinkles in cable-suspended membrane structures and provide simple reliable deployment, this study presents a multi-material topology optimization model and an effective solution procedure to generate optimal connected layout of membranes and cables. Based on the principal stress criterion for membrane wrinkling behaviour and the density-based interpolation for multi-phase materials, the optimization objective is to maximize the total structural stiffness while satisfying principal stress constraints and specified material volume requirements. By adopting the cosine-type relaxation scheme to avoid stress singularity phenomenon and the adjoint variable scheme for sensitivity analysis, the optimization model is successfully solved through a standard gradient-based algorithm. Four-corner tensioned membrane structures in different loading cases are investigated to show the effectiveness of the proposed method in automatically finding the optimal design composed of curved boundary cables and wrinkle-free membranes.

58 Shape Optimization of Shell Structure for Controlling Transient Response

Mamoru Wakasa, Masatoshi Shimoda

In this study, we propose a new approach to control transient response by optimizing the shape of a shell structure. The free-form optimization method for shells, a parameter-free shape optimization method developed by one of the authors, is extended for the transient response problem of a shell structure. The design objective is to minimize the dynamic compliance or to control the displacement at arbitrary points and times or time periods to the desired values under volume constraint. We solve this problem directly without converting the discrete equivalent static loads, which is generally employed in time-dependent optimization problems. The optimum design problem is formulated as a distributed-parameter optimization problem and the sensitivity function for this problem is theoretically derived. Based on the gradient method in the function space, we can determine the optimal free-form of a shell structure. With the proposed method, we can obtain the optimal design of a shell structure to satisfy the design objective and constraint while maintaining the surface smoothness. Some optimum design examples are demonstrated and the results are discussed at last.

59 A study of topology optimization for joint locations of automotive by using inertia relief

Takanobu Saito, Yoshikiyo Tamai, Jiro Hiramoto

The optimization method was studied to search the joint locations of spot-welding and adhesives in a automotive body made of steel sheets [1]. The key point is that the topology optimization method was applied to the optimization of joint elements using full vehicle model for improvements of vehicle performances. In addition to static stiffness using constraints, stiffness while driving is required for the body stiffness of the full vehicle. Inertia relief is known as a method for the expression of behavior while driving.

In this study, stiffness optimizations were carried out for an automotive full vehicle model by using inertia relief for stiffness while driving. Optimal targets are addition, reduction and moving of spot-welding and addition of adhesives.

The results show that the developed topology optimization method for joint locations is valuable in the optimization of automotive body made of steel sheets by using inertia relief. The optimization results of joint locations differed between the static stiffness using constraints and the stiffness using inertia relief. Optimization of location of spot-welding show the efficiency of topology method compared with conventional method and Optimization of location of adhesives show the minimum quantity of adhesive for stiffness by topology method.

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60 Numerical studies and experimental validation of topology-optimised aluminium heat sinks manufactured by additive manufacturing

Joe Alexandersen, Ole Sigmund, Knud Erik Meyer, Boyan S. Lazarov

The work covers numerical studies and experimental validation of additively-manufactured aluminium heat sinks for light-emitting diode (LED) lamps. Passive heat sinks have been topology optimised to minimise the temperature of an LED package subject only to natural convection. The topology-optimised results are compared to reference geometries supplied by project-partner AT Lighting [1]. Initial tests show that a 20-25% reduction in package temperature is obtained using topology-optimised designs with around 16% less material compared to the references.

The work builds on the initial results previously presented at WCSMO-11 [2] and utilises a density-based large scale parallel framework [3] to optimise the computationally heavy problems.
The commerical software 'COMSOL Multiphysics 5.2a' [4] is used to verify the optimised performance and to perform extensive parameter studies investigating the dependence of performance on orientation, as well as LED power.
An experimental setup, including an insulated and controllable heat source, is used to validate the optimisation results and numerical simulations. The temperature at the base of the heat sink is measured using a thermocouple and the surface temperature distribution is captured using infrared thermal imaging.

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61 Commercial Vehicle Engine Mounting Optimized Design for NVH and Durability using ATC algorithm

Yong Sok Jang, Hong Seok Chang, Jong Chan Park, Seung Won Yoo

Engine mounting insulation rubbers attach directly to the engine, which is the largest vibration source in the vehicle, and are the most important components among other NVH reduction designs. However there are other performance features such as support of engine weight and absorption of torque reaction force in addition to NVH performance. When a heavy object such as an engine of a commercial vehicle is targeted, the priority of the NVH performance is given up.

On the other hand, in the conventional engine mounting design, rubber characteristics are mainly represented by the spring constant values in the X, Y, Z directions. Even if the spring constants are presented as optimum design values, the rubber shapes are not considered. It is difficult to judge whether production is possible. Also, it is very important to secure a reliable level of performance quality in the early concept design phase. Otherwise, as the design phase continues the degree of freedom of design drastically decreases according to the layout review.

In this study, to solve the above difficulties, one of the target cascading design techniques called ATC (Analytical Target Cascading) was applied to derive the optimum design of the engine mouting according to the rubber shape. ATC is well suited to the characteristics of the automobile industry. This is a multi-stage and multi-objective optimization technique in which the whole system is devided into several subsystems and each subsystem's responses and targets are connected to the goal of the whole system.

62 Combining Anisotropic Mesh Adaptation, Heat Conduction and Topology Optimization.

Kristian Ejlebjerg Jensen

Anisotropic mesh adaptation is an established technique for accelerating the computation of front propagation problems in fluid dynamics. The most popular approach involves the computation of a metric field, which approximates the optimal mesh in a continuous sense. This metric is used to drive local mesh operations, such that the discrepancy between the discreete mesh and the optimal one is reduced in a robust way. The technique has recently been applied in the context of 3D compliance minimization, where it was shown that 1,000-10,000 nodal design variables are sufficient for a range of practical problems.

Now, we demonstrate that the technique is applicable for 2D/3D heat conduction problems, although the shell structures found in compliance minization seem better suited to anisotropic elements than the trees in classical heat conduction problems.

We adapt the mesh to minimize the 2-norm interpolation error of the continuous sensitivity and we do this before the design variable update, but after the sensitivity calculation. The design variable field is continuous (nodal), and we find that it is critical to transfer this and the sensitivity to the new mesh using exact interpolation. We show how this interpolation step can be handled as part of the mesh adaptation procedure, enabling a pure MATLAB implementation.

63 Optimization of fail-safe lattice structures

Benedikt Kriegesmann, Micah Kranz, Julian Lüdeker

The advances in additive layer manufacturing not only pushed the application of topologically optimized structures, but also the use of lattice structured. By lattice structures, we refer to structures that consist of a very large number of beam like members, often constructed from a repeated unit cell. Compared to solid structures, lattice structures show better noise and crash absorption, and they are suspect to be have a better fail-safe behavior. Certain airframe structures are required to be designed with multiple load paths to ensure that they are fail-safe. In other words, these structures need to be able to resist the design load even if one load path fails. Lattice structures typically have much more load paths than solid and therefore, they are assumed to be closer to fail-safe than solid structures. However, optimizing lattice structures without requiring fail-safe in the optimization cannot lead to a fail-safe design. If the obtained design is fail-safe, it is no optimum of the original optimization problem.
In the current work, a fail-safe optimization of lattice structures is carried out. For the optimization, unit cells are not homogenized, but their members are modelled as beam elements. This allows an engineering approach for obtaining a fail-safe design. It consist of removing one beam element at a time and optimizing the remaining structure. At the end, the maximum beam radii are used for the final design. This approach is computationally extremely expensive for lattice structures, as it requires one optimization per removed beam. In our contribution, we show that the design obtained from this approach actually does not fulfil the desired fail-safe behavior.
We suggest an alternative approach in which the fail-safe requirement is an optimization constraint. This is still computationally demanding and therefore, criteria are discussion for reducing the number of beam elements to be considered for the fail-safe requirement within the optimization.

64 Optimal design of the fiber-reinforcement of no-tension masonry walls

Matteo Bruggi, Alberto Taliercio

A novel approach is proposed to define the optimal fiber-reinforcement of in-plane loaded masonry walls, modeled as linear elastic no-tension bodies. A topology optimization formulation is presented, which aims at distributing a prescribed amount of unidirectional fiber-reinforcement over the wall, so as to minimize the overall elastic energy of the strengthened element. The adopted objective function is the same suggested by building codes to design optimal strut-and-tie patterns for reinforced concrete elements. The extension to masonry-like structures is provided by adopting a no-tension model to account for the negligible tensile strength of brickwork. Accordingly, a safe design maximizing the tensile stresses in the reinforcement layer is obtained.
The equilibrium of the no-tension body is enforced through the minimization of the elastic strain energy of an equivalent orthotropic medium with constraints on the stress state. This approach to the solution of the elastic problem can be straightforwardly embedded within the topology optimization formulation herein proposed, with the main benefit that the objective function is computed at each iteration of the optimization procedure without resorting to any demanding incremental approach.

Assuming perfect bonding between the underlying structure and the overlying reinforcement layer, both elements share the same displacement field. The reinforcing material is assumed to exhibit significant stiffness along one direction, as in the case of unidirectional FRPs. The optimal layout of the reinforcing strips is sought: both the regions to be strengthened and the local orientation of the optimal reinforcement are identified. A suitable set of stress constraints avoids the reinforcement elements to undergo compression.
Some preliminary numerical examples are shown to assess the capabilities of the proposed procedure and to identify the optimal reinforcement patterns for common types of masonry walls with openings.

65 CAD-reconstruction of non-parametric optimizations

Peter M. Clausen, Arnaud Deslandes, Claire Fritz-Humblot

One of the main obstacles in embedding topology optimization and other non-parametric optimization methods in the product design process is the lack of efficient and robust CAD-reconstruction methods for the results.
The main focus of this paper is on CAD-reconstruction of topology optimization results. The first chapter is concerned about semantics on classic parametric design and direct design. Then, we deal with various strategies for CAD-reconstructions of industry based topology optimizations, ranging from a simple manual reconstruction of a forged part (2.5D design) to complex 3D-space structures where classic construction methods are very tedious. For these latter cases, a number of new CAD-features will be presented in detail. Some of the new features are focused on free-form structures which have lately gained popularity with the current surge of use of 3D-printing industrially. Other features are more focussed on more classic design which may be manufactured more traditionally, but still with a high degree of geometrical complexity. The new features combined with some classic CAD-solid and surfacing features are combined in a single application, which to the authors knowledge is the first dedicated workbench to CAD-reconstruct non-parametric optimization results.
This article finally will show some industrial optimization examples starting from setting up a design space in the CAD-system CATIA, optimization using the optimizer Tosca and finite element solver Abaqus and reconstruction in CATIA proving that non-parametric optimization is ready for use in the industrial design process. These tools are now available in the 3DEXPERIENCE which seamlessly connects these applications to provide designers and optimization experts with a functional generative design experience.

67 Multi-objective topological design of support structure for active vibration isolation

Jianbin Du, Pingzhang Zhou, Zhenhua Lv

Active vibration isolation is one of the important measures to reduce the influence of vibration source on the surrounding environment. A typical active vibration isolation system consists of vibration source, support structure and isolators. In the conventional design of vibration isolation, many attentions have been paid to the isolators that are normally composed of springs and dampers. In this paper, we focus on the topology design of the support structure. In active vibration isolation, what we are interested in is the force transmitted to the ground.

Thus different from the conventional topology optimization of vibrational structure where the displacement response or dynamic compliance of the structure are often used as the design objective, we choose the function of the amplitude of the force transmitted from the support structure to the ground as the dynamic design objective. Meanwhile, the static compliance of the support structure is taken into account properly to ensure the design result is engineering applicable. The design problem is formulated as a multi-objective topology optimization of the support structure of the active vibration isolation system. Numerical examples on topology design of the support structure of a vibration isolation system are performed, where the vibration sources consist of two motors installed onto the plate-like support structure. Different combinations of the weights of the dynamic and static objectives are tested and the Pareto front is generated. Finally, in order to take into account the influences of different resonance frequency intervals on the vibration isolation designs, a design strategy based on the generalized incremental frequency method (GIF) is developed and applied to the problem considered. Numerical examples show that the design may produce lightweight structures with good static as well as dynamic characteristics.

68 Constrained versions of the free material design methods and their applications in 3D printing

Tomasz Lewiński, Sławomir Czarnecki, Radosław Czubacki, Tomasz Łukasiak, Paweł Wawruch

The paper deals with the free material design and its constrained versions constructed by imposing: a) cubic symmetry (cubic material design, CMD), b) isotropy with: (b1) independent bulk and shear moduli (isotropic material design, IMD), and (b2) fixed Poissons ratio (Youngs modulus design, YMD). In the latter case the Young modulus is the only design variable. The moduli are viewed as non-negative, thus allowing for the appearance of void domains within the design domain. The paper shows that all these methods (CMD, IMD, YMD) reduce to two mutually dual problems:

(P) the stress-based minimization problem in which the integrand is equal to a norm of the test stress field. The norm ——.—— involved reflects the type of the constraints imposed;

(P*) the displacement-based problem in which the virtual work is subject to maximization over the adjoint displacement fields associated with strains, the dual norm ——.——* of which is bounded almost everywhere.

Upon solving problem (P) and finding the minimizer one can determine the optimal moduli; they assume non-zero values within the material domain and they vanish outside this domain, thus allowing for cutting out the final shape from the initial design domain. Therefore, the material design methods discussed determine simultaneously: the topology, the optimal shape and elastic material characteristics. The holes appear there where the minimizer vanishes.

The YMD method has been made suitable for 3D printing. By using the inverse homogenization method the isotropic and nonhomogeneous YMD designs are replaced by equivalent discrete structures of hexagonal microstructure of varying cross sections of the ligaments. The appropriate numerical codes are prepared to make it possible to produce these fibrous structures by additive manufacturing. The produced prototypes are characterized by high stiffness with respect to the given load.

69 Innovative norm-based approaches to optimization of dynamic systems

Paolo Venini, Carlo Cinquini

System norms (H2 and H-infinity) represent a classic tool for the design of feedback control forces acting on structures equipped with a suitable set of sensors. Among the advantages of such approaches, the possibility to include load and/or structural uncertainties so as to end up with robust control strategies are worth mentioning. Typically, the structure under control is given and the design is focused on the control action, eventually including the actuator itself.

Given this scenario, this contribution presents innovative strategies for the optimal design of open-loop (uncontrolled) dynamic structures whose system norm depends on structural parameters that are to be designed so as to minimize the norm of the transfer function between the acting loads and the response quantities of interest, such as displacements and/or stresses. A gradient-based numerical scheme is set up that allows an iterative design of the dynamic structure that may be either a framed one or a plane strain 2D idealization.

Results from numerical examples are reported to complete the theoretical framework.

72 Optimal Tendon Layouts for Concrete Slabs in Buildings derived through Density-Based Topology Optimization Algorithms

Mark Sarkisian, Eric Long, Alessandro Beghini, Rupa Garai, Ricardo Henoch, Abel Diaz

Post-tensioned (PT) concrete flat-plates are highly efficient gravity systems, especially in high-rise building construction. Efficiency is particularly present in multi-span applications with orthogonal grids and regular support arrangements, reducing slab thickness and producing benefits in architecture, engineering and construction. Traditionally in the United States, following the requirements of ACI318, the system is resolved by a quasi-orthogonal tendon layout with banded strands in one direction and distributed strands in the perpendicular direction.

A novel approach to determining PT tendon layouts informed by topology optimization results has been applied by Skidmore, Owings and Merrill, LLP (SOM) to several recent projects. The optimization utilized density methods in order to find optimal load paths in a finite element continuum design space defined by the concrete floor plate. By interpreting the density distribution and orienting the PT tendons along the optimal load paths suggested by topology optimization, it has been shown that savings of 25% or more on tendon quantities can be achieved. The majority of the observed arrangements do not follow a traditional banded/distributed layout. As a result, the deflection performance is also significantly more uniform since the optimized tendon layout reduces the load path throughout the floor. This can help alleviate common issues with thin flat-plate gravity systems such as irregular floor flatness due to warping induced by PT systems and inconsistent deflection at the perimeter.

Pioneering applications of this new design approach have been evaluated for three buildings in California, and coordinated with construction teams for efficiency. This paper will discuss the design procedure from initial concepts derived from topology optimization to complete construction documents as applied to the case studies, and will create a conversation that will be of interest to both academics and practicing engineers.

73 Robust optimization using sparse data-driven polynomial chaos and trust region

Fenggang Wang, Shishi Chen, Fenfen Xiong, Jianmei Song

As a new category of polynomial chaos expansion (PCE) method for uncertainty propagation (UP), the data-driven PCE (DD-PCE) approach does not necessarily require the exact probability distribution of random inputs, and thus attracts increasing attention. To reduce the computational cost of DD-PCE, a sparse DD-PCE method has been developed by removing some insignificant polynomial terms from the full PCE model, thus decreases the number of samples for regression in computing PCE coefficients. However, when the sparse DD-PCE is applied to robust optimization, it is conventionally a three-loop process: the inner one tries to identify the insignificant terms of PCE model; the middle is UP; the outer is the search for optima, which clearly is very time-consuming for problems with expensive simulation models. To address this issue, the trust region widely used in design optimization is adopted in this paper, which is determined by the distance between two successive design points and the variation of the objective function. If the updated design point lies in the current trust region, it is considered that the significant terms of its PCE model remain unchanged compared to those of the last design point, i.e. the inner loop is eliminated at the updated design point. Meanwhile, the samples lying in the overlapping area of two adjacent sampling spaces are reused for PCE coefficient regression for the updated design point to further save the computational cost. The proposed robust optimization procedure employing sparse DD-PCE in conjunction with the trust region scenario is applied to several numerical examples of robust optimization, as well as a turbine disk engineering problems, of which the results are compared to those obtained by the robust optimization without the trust region method, to demonstrate its effectiveness and advantage.

74 An adaptive sampling method combining local approximation and multi-point strategy for reliability-based design optimization

Chen Jiang, Haobo Qiu, Liang Gao, Xiwen Cai

Kriging model has been widely used to improve the efficiency of reliability-based design optimization (RBDO) in the last few years. Two essential issues in sampling-based RBDO are the determination of sampling regions and the selection of training points. In this research, these issues are considered.
Firstly, a local approximation strategy is developed to avoid sampling points in unimportant regions. The local sampling regions are adaptively updated based on the results of reliability assessment and RBDO in every optimization step. Secondly, a multi-point sampling strategy is developed to decrease the iterative steps in the whole optimization process. It considers not only the statistical information of kriging model but also the probability density function of design variables. Moreover, the multi-point sampling strategy can guarantee that the local approximation is not trapped in the local optimum. In conclusion, combining these two strategies makes it possible to improve the efficiency and maintain the accuracy at the same

time. Several examples are used to demonstrate the results of the proposed method compared to other existing methods.

75 Optimization approach for free-orientation of a laminated shell structure with orthotropic material

Yoshiaki Muramatsu, Masatoshi Shimoda

Shell structures have been widely utilized in various industrial products. From an economic point of view, weight reduction is strictly required in the structural design of cars, aircrafts and so on. The usage of composite materials, such as carbon fiber reinforced plastics (CFRP), in shell structure is one of the solutions to meet the requirement since they have higher mechanical performances than metals. Especially, orthotropic materials can be used for making specific stiff directions of shell structures.
In this study, we propose a material orientation free optimization method for optimum design of shell structures and laminated composite shell structures consisting of orthotropic materials. We consider a single objective in term of the compliance in the present work, and minimize it under the state equation constraints. The material orientation distributions in all each layers are determined as design variables. The optimum design problem is formulated as a distributed-parameter optimization problem, and the sensitivity function of the orientation variation is theoretically derived. The optimal orientation variations are determined by using the H1 gradient method, where the sensitivity function is applied as the driving force to obtain the smooth material orientation distribution. In particular, after we derived the sensitivity function, we transfer it to the internal heat generation and determine the orientation variation by using the Poissons equation for fictitious-heat transfer analysis to ensure the continuously distribution of the material orientation. The optimum design examples show that the proposed optimization method can effectively obtain the optimum material orientation with free distribution and the minimum compliance.

76 Dynamic Behavior of Hanging Truss Having Shape Memory Alloy Wires (From the Optimization Viewpoint of Vibration Isolation and Attenuation)

Xuan Zhang, Kazuyuki Hanahara, Yukio Tada

Attenuation and isolation are typical means to cope with the environmental vibration. In this research, we consider a kind of truss structural system which is expected to possess both of the capabilities. Vibration attenuation is achieved by utilizing the shape memory alloy (SMA) wires characterized by its hysteretic loop of the pseudo-elasticity in relatively high temperature condition. Vibration isolation is realized based on relatively low stiffness of the wire members as well as the hanging configuration of the truss structural system itself; that is, the truss structural system in hanging configuration is able to demonstrate the property of the pendulum. In the current study, we deal with a hanging truss structural system having SMA and ordinary wire members. Both types of wire members have different mechanical characteristics; by combining these two types of wires, the attenuation and isolation capabilities and the stability of the hanging truss against the environmental vibration can be simultaneously achieved. We examine the abilities of this truss structural system through the calculations of the dynamic equations. In order to tackle nonlinearity of such kind of dynamic problems, a time integration method coupled with nonlinear iterative method is introduced. A combinatorial optimization problem is formulated and is solved by multi-objective genetic algorithm. Optimal configurations of the truss structures and the corresponding dynamic behaviors are discussed.

78 Topology optimization of planar linkage mechanisms involving gear components

Neung Hwan Yim, Seok Won Kang, Yoon Young Kim

The topology optimization of planar linkage mechanisms for path generation is an interesting and important research subject, but studies so far have been concerned with the synthesis of mechanisms having joints only. To generate more general paths by a synthesize mechanism, one may need to additionally consider elements other than joints, such as gears. The consideration of gear elements that are kinematically quite different from joints poses considerable challenge for the topology optimization of planar mechanisms. The objective of this work is to solve the topology optimization of planar linkage mechanisms involving gears and revolute joints. Specifically, this study aims to develop a formulation suitable to determine the existence and location of gears as well as link-joint connectivity.
The underlying discretization model is based on the spring-connected rigid block model (SBM) for this study. However, this model alone cannot be used for the synthesis of gear elements. So, we propose the so-called geared block model, an additional model suitable to represent gears; with the geared block, one can simulate geared motion. To facilitate the simultaneous synthesis of dissimilar mechanical elements, joints and gears, we put the geared blocks (GBs) over the spring-connected blocks (SBs) and connect them by zero-length springs the stiffness of which is controlled by real-valued design variables. If these design variables reach their upper or lower bounds, one can simulate geared motion or motion without any gear. Along with zero-length springs that connect SBs to each other, the springs connecting GBs to SBs form the design variables. Because the design variables are real-valued, a gradient-based optimizer can be used. The problem to find the gear location and ratio is also considered and some practical ideas are tested. Several numerical problems are considered and the findings from this study will be summarized.

79 Concepts to couple CAD and non-parametric shape optimization

Nick Stoppelkamp, Ekaterina Kovacheva, Peter M. Clausen

Complex geometrical shapes are now also possible to manufacture in an industrial setting, due to a recent surge in additive layered manufacturing (ALM or 3D-Printing). Often these complex geometries are created using subdivision surfaces. When embedding these surfaces in a parametric optimization setup, typically only a relatively small amount of parameters can be varied, leading to a restricted design domain. In contrast the other widespread approach, non-parametric optimization (finite element node positions are design variables), acts efficiently with many design variables. A main drawback is the cumbersomely fitting of the CAD model to the optimization result.

In this paper, a method to couple subdivision surfaces with industrial used non-parametric optimization is presented. The subdivision control points act as design variables and they get linked with the finite element nodes. This enables us to work with the solutions and sensitivities for the finite element mesh. The paper shows how to create a mapping between the 3D geometry space spanned by the subdivision surfaces and a 3D finite element mesh. Furthermore, the role of this mapping in deriving sensitivities with respect to the subdivision control point positions is carved out. Challenges and disadvantages are discussed. The potential of the method is shown using some real world examples from industries.

80 An Element Deactivation and Reactivation Scheme for the Topology Optimization based on the Density Method

Robert Dienemann, Axel Schumacher, Sierk Fiebig

Topology optimization (TO) results based on the homogenization or density method highly depend on the discretization of the design space. The smallest possible dimension of the optimized structure is one element edge length. If the mesh can be refined, smaller design features can be represented and thereby the performance of the optimized structures can be improved. But the mesh refinement is limited by the computational cost of the Finite Element Analysis (FEA). The aim of this contribution is the reduction of the computation time due to a reduction of the FE-model. Therefore a scheme for the density method is introduced, which deactivates low dense elements and enables a reactivation of important elements. These low dense elements usually do not have a mechanical importance and they also have zero sensitivity considering compliance, stress or nodal displacements using the SIMP-approach (Solid Isotropic Material with Penalization of intermediate densities). Nevertheless all elements of the design space are usually included in the FEA during the TO. Our approach reduces the number of active elements continuously with the iterations as the design converges to a black-and-white-design. The presented approach is similar to the algorithm of Bruns and Tortorelli (2003), but their approach is limited to density filtering. Furthermore our contribution shows how to cope with problems of the element deactivation. The deactivation/reactivation-scheme is presented considering compliance, stress, nodal displacement and frequency TO problems showing the advantage of time saving, especially of structures with low volume fraction. Therefore we use this scheme for the TO of shell structures based on continuum elements with manufacturing constraints.

Bruns, T.E.; Tortorelli, D.A. 2003: An element removal and reintroduction strategy for the topology optimization of structures and compliant mechanisms, Int. J. Numer. Meth. Engng 57, 14131430

81 On a Nash game formulation for robust structural optimization and its numerical solution using a decomposition method

Henrik Alm Grundström, Carl-Johan Thore, Anders Klarbring

Robust structural optimization can be formulated as a two(or more)-person mathematical game between a "designer", trying to achieve a structure which is optimal in some sense, and "nature", seeking the worst possible conditions to impose on the structure. For the special case of structural topology optimization (TO) under load-uncertainty, the designer solves a standard TO problem for a fixed load – the ”design-problem” – while nature solves another optimization problem – the ”load-problem” – to find the worst load for a given design. Choosing the compliance as the objective function for both players one can consider either a min-max (or Stackelberg) formulation or a Nash game. The focus here is on the latter type, and in particular we study the use of so-called decomposition methods to obtain numerical solutions. When applied to our Nash game, such methods solve the design- and the load-problem in an alternating sequence, hopefully converging to a Nash equilibrium (consisting of a load(s) and an optimized structure which is robust in the sense that it performs no worse for any other load realizable in the game). Decomposition methods for finding Nash equilibria are attractive since they are very easy to implement and may allow for straightforward parallelization. However, there are at least two major issues that must be dealt with: (i) existence of Nash equilibria, and (ii), when existence is assured, convergence to such points. We show here using numerical examples with trusses and discretized continuum structures that, when equilibria exist, convergence can be achieved, but sometimes requiring penalization of design and load variations to avoid oscillatory behaviour of the decomposition method. We also give examples which seem to lack equilibria – or at least where the robust design obtained from the corresponding min-max formulation is not an equilibrium-design – leading to non-convergence of the algorithm.

82 Eigenmode optimization revisited

José Carlos Bellido, David Ruiz, Alberto Donoso

Nowadays, eigenfrequency optimization problems in topology optimization are widely studied and quite well understood. In particular, several good-performing methods are available for computing eigenfrequency derivatives with respect to the design variables, necessary for gradient-based optimization algorithms. Further, this is so even for the repeated eigenfrequencies case, in which the eigenfrequency is no differentiable with respect to the design variables, and, in principle, non-smooth optimization algorithms would be required. Whereas eigenfrequency optimization problems are very common, eigenmode optimization problems are very rare in the literature. Eigenmode sensitivity analysis has been addressed in several papers. In the case of eigenmodes corresponding to simple eigenfrequencies the problem is well understood and there are efficient algorithms for derivatives calculation. For eigemodes corresponding to multiple eigenfrequencies, there exists only certain eigenmodes (adjacent) which are differentiable. No other eigenmodes are differentiable, and this is an issue if one tries to follow a given mode shape during the optimization process or for mode tracking. Motivated by an investigation on the design of modal piezoelectric sensors/actuators, for which both cost and constraints depend on eigenmodes that followed predetermined modal shapes, we have proposed an algorithm for this non-differentiable situation that works out. In this talk we will deepen in this issue, analyzing the mathematical foundations of our algorithm and showing how our algorithm can be successfully used in other physical situations.

83 Topology Optimization of a Box-beam Structure Considering Crash Loadings and Rate-dependent Nonlinear Material Behaviors and Using Equivalent Static Loads

Cheol Kim, Mohammadmahdi Davoudi

Since crash box structures are important elements in a vehicle structure to absorb the crash energy, the design optimization to meet less weight and higher safety has of great value. However, due to the high nonlinearity in material behaviors and dynamic responses, to satisfy the dual goals is very controversial. The structural optimization with non-linear dynamic responses is generally classified into the gradient-based optimization, the non-gradient-based one, and the equivalent-static-loads method. Practical or large-scale examples are seldom found to be used by gradient-based optimization because of the computational cost. Additionally, optimization results obtained by non-gradient-based optimization are highly dependent on the number of samplings, which is related to the number of design variables. In order to overcome these difficulties, a combination of equivalent-static-loads (ESLs) and gradient-based linear static structural optimization is applied. The ESLs are the loads that generate the same response field of linear static analysis as that of nonlinear dynamic analysis at each time step. The ESLs are imposed as external loads to do the linear static structural optimization. This process continues until meeting the convergence criterion. The structural optimization of a nonlinear dynamic problem with highly nonlinear geometry and material behaviors with rate dependent plasticity, damage initiation, damage evolution up to the element removal problem is expanded. The research goals are to obtain an efficient optimum topology of thin-walled structure under the axial crush and to control its crashworthiness by using the ESLs method. The obtained topology optimization results would be the real clue to design the most efficient and light crash box structure under the same working condition. Furthermore, the methodology can be applied to the structures with highly nonlinear behaviors in terms of material, geometry, vibratory and combined crash loadings.

84 Topology optimization of repair patches for primary aircraft structures by minimizing energy release rate

Anders Klarbring, Bo Torstenfelt, Ulf Edlund, Peter Schmidt, Kjell Simonsson, Hans Ansell

Fatigue cracked primary aircraft structural parts that cannot be replaced need to be repaired by other means. A structurally effective such repair method is to use adhesively bonded patches or reinforcements. The following paper considers optimal design of such patches. Two topology optimization formulations are compared. Firstly, a standard density based stiffness optimization is performed, where the cracked aircraft structure is fixed while the adhesively bounded patch is subject to topology optimization. A stiff structure is likely to be effective in that crack opening will be diminished by the repair. However, a likely even better, more direct and to our knowledge new topology optimization approach is to replace the stiffness objective by the energy release rate and such a method is developed in the paper. The energy release rate is defined as the negative of the crack extension derivative of the structure's potential energy and can be effectively calculated by use of finite element shape sensitivities, without the need for, e.g., J-integral formulas. In a first order optimization method we also need the sensitivity of the energy release rate with respect to the topology density variables. It is shown that, by use of an adjoint method, these can also be easily calculated. Both optimization formulations are solved by optimality criteria iterations where the stiffness sensitivity used in the first formulation is replaced by the sensitivity of the energy release rate in the second formulation. Numerical results show that the optimal energy release rate, and thus the fatigue resistance, is substantially lowered by the change of objective function. It may also be noted that the energy release rate sensitivity is not restricted in sign, as is the stiffness sensitivity, meaning that removing material can make the objective better, which is also seen in the numerical results.

85 Optimization of Concrete Cable-stayed Bridges with Discrete Design Variables

Luis Simões, Alberto Martins, João Negrão

This work presents a procedure for finding the discrete optimum design of concrete cable-stayed bridges. The behaviour of this type of structures is governed by the stiffness of the load bearing elements (towers, deck and cable stays) and the cable force distribution. In the concrete bridges, the stresses and deformations are signifficantly influenced by the construction sequence and concrete time/dependent effects. Furthermore, the geometrical nonlinear behaviour which arise when dealing with cables in large and flexible structures must be considered in the analysis. A finite element approach is used for the structural analysis. It includes a direct sensitivity analysis module which provides the structural behaviour responses to changes in the design variables. The optimum design of concrete cable/stayed bridges involves a signifficant amount of design variables and objectives. The minimization problem is stated as the minimization of stresses, displacements and the bridge cost. To solve the continuous optimum design problem an equivalent multi-criteria approach was used, turning the initial problem into an equivalent sequence of unconstrained convex scalar optimization problems from which a Pareto optimum can be found. This is followed by the rounding up or down of the continuous cross section variables to the nearest available discrete sections to obtain a discrete solution. Once the design variable are fixed the solution is then improved by optimizing the cable installation forces (continuous variables) to meeet the stress and displacement criteria. If the solution is unfeasible, the segmental method which employs linear programming is used to find the discrete sizing variables which need to be modified. A concrete cable-stayed bridge example is presented to illustrate the features of the proposed procedure.

86 Topology Optimization of Thin-walled Structures Under Static/Crash Loading Case in the Hybrid Cellular Automaton Framework

Duo Zeng, Fabian Duddeck

Crashworthiness design and optimization is of great importance in the automotive industry. However, due to the high computational cost and numerical noise, crashworthiness topology optimization is not studied so intensively. In this paper, a relatively new method, the Hybrid Cellular Automata for Thin-walled Structures (HCATWS) is used in its improved version. In particular, its applicability is extended from structures with an initially regular grid to structures with different size of cells (sets of a higher number of finite elements). The corresponding modifications of the algorithm are discussed here. This also affects the updating rules used in the improved version; hence, the theory is revised and modified where necessary. In the outer loop of the HCATWS, bi-section search within limited length is used to define the target mass. In the inner loop, HCATWS utilizes proportional updating to redistribute the mass for each cell. Then mass correction is conducted to make sure the real mass converges to the target mass. Here the different sizes of the cells need to be considered. As applications, one linear static case is studied to demonstrate efficiency of the approach. Then, additional crash cases using nonlinear dynamic FEM are considered. Finally, the potential of using this approach for identification of optimal cross-sections of structures originating from Additive Manufacturing (AM) is explored. Here, it is important that optimized topology results from HCATWS are more easily manufactured compared to those obtained by traditional element-based, i.e. voxel-based, topology optimization.

87 A Platform Approach for Topology Optimization to Overcome the Gap between Geometry and Simulation

Michael Werner, Gergana Dimitrova

Topology optimization methods are valuable industrial design tools helping engineering departments to come up with lightweight conceptual design proposals. The ongoing rise of additive manufacturing (AM) for series and not just prototype production has pulled generative design to the forefront of design and manufacturing solutions. The typical organic shapes have become a symbol for innovative product designs now being more easily producible with the help of AM.

This paper focuses on the three major challenges having prevented so far a wider adoption of topology optimization as a standard design tool: 1. manufacturability of optimized designs 2. optimization usage in the very beginning of the overall design process 3. interpretation of optimized design proposals to gain valid CAD geometries

As of today topology optimization is usually applied in the simulation department when the CAD group already came up with an initial design concept. Thus important design decisions are not driven by simulation. Democratization of simulation powered by a platform approach helps to unfold the full potential of topology optimization. Full connectivity of data and collaborators enables processes where a design engineer starts a preliminary design concept study and continuously hands over the work to the colleagues in the simulation group. There, a mechanical analyst continues working on the same data adding more accurate and complex physical modeling. Since the simulation is linked with its underlying geometry the new proposed design can easily be incorporated into a valid and parameterized geometry. With this the interpretation and reconstruction of the topology optimization results become much easier than before helping to close the gap between geometry and simulation. The paper highlights the possible efficiency gains for industrial applications of topology optimization and compares the use of a traditional CAD-FEA-Optimization-CAD process with an integrated platform approach.

88 A study on the design of large displacement compliant mechanisms with a strength criteria using topology optimization

Daniel Milbrath De Leon, Juliano Fagundes Gonçalves

In this work, large displacement compliant mechanisms are designed using a gradient-based topology optimization formulation. Since such devices are designed to fulfill a kinematic task, take into account a nonlinear approach is very important. Besides that, as the mechanism strain is used to achieve the kinematics, a strength criteria must be included in the optimization problem. The use as well as the need of application of geometrical and/or material (compressible hyperelasticity) nonlinearities are discussed as well as the effectiveness of the stress constraint. The method of moving asymptotes is applied for the design variables updating. The derivatives are calculated analytically, by the adjoint method. In order to ensure topologies as near as possible to 0/1 solution, projection filtering techniques are applied. The well-known hinge problem in compliant mechanisms is also discussed and the role of both nonlinear analysis and stress constraint are discussed by means of benchmark examples. Eventually, the results are compared with linear formulation.

89 Finite-life fatigue topology optimization using a density approach

Jacob Oest, Erik Lund

In this work, structural optimization by minimization of mass using 2D topology optimization with finite-life fatigue constraints is solved using the Method of Moving Asymptotes. The topology optimization problem is formulated using the density approach, and the physics are modeled using linear finite element theory. The fatigue damage is estimated by Palmgren-Miners linear damage hypothesis in combination with S-N curves and the Sines fatigue criterion. By using aggregation functions and the accumulative nature of the fatigue constraint, analytical sensitivities can be determined effectively using the adjoint method. In fact, the amount of adjoint problems that must be solved is independent of the applied load spectrum in the quasi-static fatigue analysis of the structure. Thus, large load series can be applied with minimal additional computational cost.

Benchmark optimization problems are solved for fatigue constraints and compared to designs optimized for a static von Mises yield criterion. The presented method is valid for proportional loading conditions and linear elastic material behavior, and it is straightforward to implement in a traditional stress-based topology optimization framework.

It is important to have a generic method for fatigue optimization, as numerous different fatigue criteria are being used in the design of engineering structures and components. With the aforementioned modeling assumptions, other stress-based fatigue criteria can be applied directly in this optimization formulation without increasing the amount of adjoint equations. Additionally, complex S-N relationships that account for e.g. weather conditions or surface treatments can be applied. The formulation can also be used for 3D problems.

90 Fatigue Sensitivities for Sizing Optimization of Shell Structures

Nikolai Gerzen, Peter M. Clausen, Claus B. W. Pedersen, Shyam Suresh

The present work is on non-parametric sizing optimization of shell structures for fatigue. Many shell structures are subjected to high cyclic loading for long time series which often causes the fatigue design requirement to be one of the most critical design requirements of the entire structure. The fatigue of shell structures is dominated by high stress concentrations at the welded joints between various shell parts. The present fatigue calculation is based upon rainflow counting and linear superposition of non-proportional loading histories applied to the shell structures. Accordingly, the fatigue of the welds is strongly coupled to shell thicknesses being the sizing design variables.
The fatigue sensitivities are determined using a semi-analytical adjoint sensitivity approach as the number of thickness design variables in non-parametric sizing optimization is large and the request of using mathematical programming for non-parametric optimization. The theoretical aspects of the corresponding semi-analytical adjoint sensitivity analysis and some practical assumptions are discussed. The validation of the approach and the assumptions are verified by comparing the semi-analytical sensitivities to sensitivities determined using finite difference.
The potential of the presented approach is demonstrated on a number of small verification examples as well as selected industrial applications. A typical optimization setup is to minimize the mass subject to weld fatigue constraints. Furthermore, the present approach for fatigue sizing optimization is integrated into an industrial workflow allowing the fatigue sizing optimization to be combined with structural design targets of static analysis, modal analysis and frequency response analysis, respectively. Jacket structure where the shell thicknesses are optimized and the mass is minimized subject to both fatigue constraints and modal eigenfrequency constraints are possible examples.

91 ALM Overhang Constraint in Topology Optimization for Industrial Applications

Marcel Hoffarth, Claus Pedersen, Nikolai Gerzen

One of the manufacturing processes getting the most attention in the last years is the additive layer manufacturing (ALM) also known as 3d printing. ALM is the ideal manufacturing process for structural components having complex geometrical descriptions often obtained when designing using topology optimization.
ALM brings its own set of model requirements. Major aspects introduced by the printing process are usually residual stresses, material anisotropy and the printability of overhanging structures. Generally, overhanging structures are printable up to a certain minimum angle, depending upon the material and printing technique. Overhangs which undercut this critical angle will require additional support during the manufacturing process. Afterwards these support structures must be removed and the surface requires additional costly manufacturing post processing. To avoid critical overhang the present work addresses an approach constraining the geometry in the conceptual topology optimization design stage by adding an overhang constraint in the topology optimization formulation. This overhang constraint is integrated in an industrial design environment. Thereby, the constraint can be applied to

unstructured meshes (e.g. triangular or tetrahedral) and to various objective functions and constraints typically applied in industrial applications (e.g. minimize mass with stiffness, strength and modal eigenfrequency constraints) with various overhang degrees. Additionally, the optimization solution is integrated with a general non-linear FE-solver allowing the user to include advanced contact modeling, various element types, material and geometrical non-linearities being a standard requirement for industrial design solutions having an overhang constraint.
Several industrial applications will be demonstrated comparing the differences in structural layout and structural performance for topology optimized designs with and without manufacturing constraints.

92 Structural Multi-objective Optimization of SPB LNG Tanks Based on Approximate Model and Genetic Algorithm

Yuan Wang, Deyu Wang

SPB (Self-supporting Prismatic-shape type B) LNG tanks are designed with internal bulkheads and girders to reduce liquid sloshing resonances in the tanks. The present research aims to give a structural multi-objective optimization for the SPB LNG tanks under sloshing pressures. Sloshing coefficient is defined to show the complicated effects of internal girders on sloshing in tanks. The structural multi-objective optimization model of SPB LNG tanks is established in ISIGHT with two objectives including the sloshing coefficient and the structural weight of tank. A high-accurate approximation model is established with the methods of DOE (design of experiments) and RBF (Radial Basis Functions) to save the time costs of finite element analysis process in optimization. Then the optimization is performed by three kinds of multi-objective genetic algorithms including NSGA-II, NCGA and AMGA. Finally, an improved scantling design of SPB LNG tanks is achieved and verified. Numerical results show that AMGA is the best algorithm for this problem compared with other algorithms. Furthermore, the sensitivity analysis of design variables to the objectives is carried out, which provides a reference for the structural design of SPB LNG tanks.

93 Isogeometric Shape Optimization on Triangulations

Cunfu Wang, Songtao Xia, Xilu Wang, Xiaoping Qian

The paper presents a Bezier triangle based isogeometric shape optimization method. Bezier triangles are used to represent both the geometry and physical fields. Due to the use of Bezier triangles, this shape optimization method is applicable to structures of complex topology and allows for local refinement. For a given physical domain defined by B-spline boundary, a coarse Bezier triangular parameterization is automatically generated. This coarse mesh is used to maintain parameterization quality through positivity of Jacobian ordinates of the Bezier triangles and to move mesh by solving a pseudo linear elasticity problem. Then a fine mesh for isogeometric analysis is generated from the coarse mesh through degree elevation and refinement. As the fine mesh retains the same geometric map as the coarse mesh, we can guarantee mesh validity during the shape optimization with constraints on the Jacobian ordinates of the coarse mesh only. This bi-level mesh allows us to achieve high numerical accuracy of isogeometric analysis at lower computational cost on mesh validity control and

mesh movement. Due to the use of B-spline boundary, the optimized shape can be compactly represented with a relatively small number of optimization variables. By representing the squared distance between two Bezier curves as a Bezier form, a distance check scheme is also introduced to prevent intersections of design boundaries and control the thickness of structural connections. Numerical examples are presented to demonstrate the efficacy of the proposed method.

94 A New Algorithm for Material Optimization Applied on a Two-Scale Optimization Approach for Lattice Structures

Thomas Guess, Michael Singl

We present an algorithm, based on the idea of sequential convex programming [1], and its application in two-scale material optimization using lattice structures. In each major iteration we solve a convex problem depending on the material tensor. The nonlinearities of the material tensor parameterization are treated in a subproblem which can be solved globally optimal and efficiently, due to the block separability. This combination of a convex problem written in the material tensor and globally solved subproblems leads to a very efficient algorithm for most material optimization problems.

We apply the algorithm on a coupled two-scale material optimization problem in linear elasticity, based on [2]. For a cross shaped lattice base cell, we calculate the homogenized material tensor on a microscopic scale. We vary the shape of the base cell by thickness and rotational design parameters. For computational efficiency, we precompute a homogenized material catalog for a discretized set of design values beforehand. During the solution of the subproblem, we interpolate the macroscopic material tensor for the design parameters on each finite element by a C1 interpolation model from the precomputed material catalog.

We discuss theoretical properties of the new algorithm. Additionally, we focus on the effectiveness of the algorithm in terms of computational time as well as quality of the solution with respect to global lower bounds and alternative parametrizations by a various numerical examples.

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96 An optimal configuration of an aircraft with high lift configuration using surrogate models and optimisation under uncertainties

Joachim Rang, Wolfgang Heinze

Nowadays many simulations are computationally expensive, which is disadvantageous if one is interested in the quantification of uncertainties, parameter studies or in finding an optimal design. Therefore often so-called surrogate models are designed, which are a good approximation of the original model, but computationally less expensive.

In this talk we first look for an approximation method to design a surrogate model for the simulation of a civil aircraft with high lift configuration. Such aircrafts have the advantage that only small runways for starting and landing are necessary. A first result, which is presented in this talk, is a configuration where the direct costs are minimised. For the optimisation 7 parameters are chosen, for example, the Mach number in the cruise flight and the area of the wing.

In a second step 29 uncertainties from the areas structure, aerodynamics, means of propulsion, and compressor systems because several input parameters are not exactly known. Therefore we look for a robust configuration which causes minimal costs and where the needed runway is limited to a certain length.

97 Frequency Response Characteristics of 2D Wings in Uncertain Environments: A Random Matrix Theory Approach

Aditya Vishwanathan, David Munk, Gareth Vio

Whilst structural design processes in engineering have been extensively developed, the additional consideration of uncertainty quantification (UQ) provides a more holistic forecast on its long term sustainability. UQ methods such as Polynomial Chaos Theory have received attention in numerous fields within engineering for its ability to approximate statistical moments with good accuracy and with low computational expense. This study explores a probabilistic approach to analyze frequency response in 2D wings facilitated by Random Matrix Theory (RMT). This UQ method has not been explored thoroughly within the aerospace sector. Uncertainties are enforced on the length, width and Young's modulus of two wings varying in geometry and the natural vibration mode characteristics are determined via finite element modeling. Baseline characteristics are compared to an approximation derived from RMT and the worst case scenarios. It was found that RMT provided a good estimate of both the frequency and magnitude shifts of the vibrational modes under the enforced uncertainty. The more complex geometry was found to be more robust to the imposed variations, and RMT was able to capture this behavior effectively.

98 Tensegrity Topology Optimization by Force Maximization on Arbitrary Ground Structures

Ke Liu, Glaucio H. Paulino

This paper presents an optimization approach for form-finding of tensegrity structures based on graph theory. The formulation relies upon a mixed integer linear programming, associated to ground structures, through force maximization that usually generates stable and symmetric structures. The method seeks for the proper topology of the tensegrity given a fixed geometry, providing a perspective interpretation of the tensegrity design from a geometric point of view. Borrowing ideas from computer graphics, we allow "restriction zones" (i.e. passive regions in which no geometric entity should intersect) to be specified in the underlining ground structure.

Such feature allows the topology design of tensegrity in actual engineering applications, such as robotics, in which the volume of the payload needs to be protected.

99 Experimental verification of topology optimized lattice using metal additive manufacturing

Akihiro Takezawa, Kazuo Yonekura, Yuichiro Koizumi, Makoto Kobashi, Mitsuru Kitamura

Microstructural shape optimizations of material are very active topic in the field of topology optimization (TO) from the early stage. However, the complicated shape of the hard to be implemented by conventional manufacturing techniques. Thus, few experimental verification was performed which is crucial for putting these material to practical use. This issue can be solved by recent additive manufacturing (AM) technologies. It can fabricate porous metals with precise internal pore structures and effective performance.

In this research, we derived high stiffness lattice structure based on homogenization method and TO and verified these performance experimentally utilizing AM. The design domain was represented by SIMP approach and the density function was updated by the phase field method which is a level set like boundary variation method. The design maximizes the effective bulk modulus and isotropic stiffness, and the performance is compared with Hashin-Shtrikman (HS) bounds. As a manufacturing restriction, powder removing holes must be introduced to the optimized structure. They are fabricated via selective laser melting of maraging steel and electron beam melting of Ti-6Al-4V titanium alloy.

The stiffness and strength of these test pieces were measured by compressive testing. The errors between the FE analysis and experiments were less than about 10%. In the comparison with the conventional porous material, the measured stiffness are slightly (just less than 20%) higher than conventional (not optimized) porous metals. However, the optimized structures shown much higher strength than that of conventional ones. Thus, stiffness optimized lattice can have an engineering utility as a high strength material with tunable stiffness.

100 Systematic structural design for frequency response applications using topology optimization

Hong Kyoung Seong, Jeonghoon Yoo

Topology optimization for frequency response (FR) problems was introduced to minimize the dynamic response of a structure under harmonic force oscillation [1]. Previous researches on FR problems have focused on minimizing dynamic response in a certain frequency range and reducing the computation time. Moreover, topological design regarding dynamic behavior has mainly treated the eigen-frequency maximization problem and it is hard to find works to include the resonance frequency and the bandwidth in the design objective function directly. To consider the eigen-frequency change and the dynamic compliance simultaneously in topology optimization, an innovative scheme for FR applications is required. In this study, a FR function is mapped onto a probability distribution function (PDF) and the resonance frequency and the bandwidth for FR problems are defined using the PDF concept. The mean value of random variables in the PDF becomes the resonance frequency while the variance value, which measures the spread of the response from the mean value, represents the bandwidth of the FR function. Moreover, the mean and the variance may be combined with dynamic compliance to construct a multi-objective function for FR applications. The phase field design method is employed to implement topology optimization [2]. The finite element analysis was performed by using the commercial package COMSOL and the optimization process was programmed using Matlab programing.

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101 Reliability-based Topology Optimization for Continuum Structures with Non-probabilistic Uncertainty

Jing Zheng, Zhen Luo, Chao Jiang

A non-probabilistic reliability-based topology optimization (NRBTO) method for continuum structures is proposed for structures with correlated interval parameters. Based on multidimensional parallelepiped (MP) model, a topology optimization model is formulated to minimize volume of structure under displacement constraints. An equivalent efficient decoupled procedure is given based on the performance measurement approach (PMA) and the sequential optimization and reliability assessment (SORA). A numerical example is used to demonstrate the effectiveness of the proposed method.

102 Condensation techniques for multiscale topology optimization and additive manufacturing

Emmanuel Tromme, Atsushi Kawamoto, James K. Guest

Topology optimization provides tremendous opportunities to create highly efficient components and systems tailored for a specific application. It can be applied to design an optimal structure as well as an advanced material that exhibits interesting properties by considering a gross idea of potential future uses.

This research is dedicated to multiscale topology optimization and consists in designing simultaneously the structure and the material, i.e. the structural layout is optimized at the macroscale and an architected material is designed at the microscale. Designing at both scales simultaneously opens up the design space as the material can be directly optimized according to the functional needs at the macroscale. As a consequence, the resulting approach can lead to lighter and more efficient structures.

Homogenization theory is generally adopted to bridge the scales. This method computes effective material properties of a microstructure that are subsequently used to determine the macroscale structural performance. This step is essential to keep a reasonable computation time since a very fine mesh is needed to capture microstructural details.

Additive manufacturing technologies provide a new means of fabricating very complex topology-optimized designs. However, the homogenization theory assumes an infinitely small size of the microstructure whereas a finite size must be considered for manufacturing. As a result, connectivity between microstructures may not be ensured.

In this work, a method based on condensation techniques is proposed to perform multiscale topology optimization. It follows that the connectivity between space-varying microstructures is naturally fulfilled. Also, condensation methods lessen the computation time. Several examples illustrate and validate the proposed method. A discussion is carried out on the practical use of such optimized designs.

103 Multivariate Density Estimation Using Kernel Density Estimation and Copulas

Yoojeong Noh, Jimin Hong, Young-Jin Kang, O-Kaung Lim

In engineering problems, various input variables such as material properties have correlation and copulas, which are parametric multivariate models, have been used to model their joint distribution. The joint distributions modeled by copulas are used to carry out reliability analysis and reliability-based design optimization. For identification of copulas, goodness-of-fit(GOF) test such as Cramr-von Mises test and model selection method such as Bayesian method have been commonly used. However, some correlated variables cannot be modeled by the parametric models, and thus, it is necessary to develop a nonparametric multivariate density estimation method. In this study, a nonparametric multivariate density estimation method was proposed using multivariate kernel density estimation (MKDE). To determine the optimal bandwidths of the multivariate kernel functions, the Markov Chain Monte Carlo simulation method was used[1]. Through simulation studies, the obtained statistical models were compared for different types of kernels, bandwidths, and the number of data. In addition, in real applications, it is difficult to determine whether a parametric modeling method provides accurate models or a nonparametric modeling method provides accurate models, so that an integrated statistical modeling method that combines the copulas and MKDE was proposed in this study. Through simulation tests and simple reliability analysis problems, the obtained results using copulas, MKDE, and an integrated statistical modeling method were compared.

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104 Development of an Integrated Statistical Modeling Method for Insufficient Data

Young-Jin Kang, O-Kaung Lim, Yoojeong Noh

Statistical modeling of input variables is necessary to carry out statistical analysis such as reliability analysis. However, in engineering problems, it is difficult to obtain accurate statistical models because there exist insufficient data. Therefore, it is necessary to develop accurate statistical modeling methods for very limited data.

Statistical modeling methods are categorized as parametric and nonparametric methods. In the parametric methods, the Goodness-of-fit tests and model selection methods are commonly used, and the sequential statistical modeling(SSM) method that combines two methods has been recently developed [1]. In the nonparametric methods, the Kernel density estimation(KDE) is generally used, and the KDE with bounded data(KDE-bd) methods that combine the KDE and the interval approach has been recently developed [2]. It was shown that the SSM and KDE-bd improved accuracies of statistical models comparing with other traditional methods [1,2].

However, it is difficult to determine in which cases two methods need to be used for given data. Additionally, the KDE-bd can be used in sampling-based reliability analysis methods, but it cannot be used in analytical reliability analysis methods. Therefore, in this study, an integrated statistical modeling method, which serially combines KDE-bd and SSM methods, is proposed to obtain more conservative statistical model than the one from SSM and more accurate than the one from KDE-bd.

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105 Large scale topology optimization of bridge girders in cable supported bridges

Mads Baandrup, Niels Aage, Ole Sigmund

This work utilizes the topology optimization method to study the optimal structure of bridge girders in cable supported bridges. The current classic orthotropic box girder designs are limited in further development and optimization, and suffer from substantial fatigue issues. A great disadvantage of the orthotropic girder is the loads being carried one direction at a time, thus creating stress hot spots and fatigue problems. A new innovative design concept, based on topology optimization, thus has the potential to solve many of the limitations of the current concept.

The scientific simulation software PETSc is used together with the topology optimization framework. The highly detailed structures and fine mesh-discretization permitted by large scale topology optimization reveals new design features and previously unknown effects. The results show the potential of completely new design solutions for bridge girders in cable supported bridges. The new designs differ significantly from the classic orthotropic box girders.

A typical section of the bridge girder in the recently built 2682m long suspension bridge Izmit Bay Bridge is used as the basis for the study. The dimensions of the design domain are 25m length, 30.1m width and 4.75m height. To discretize this huge domain into reasonable element sizes indeed requires very large scale topology optimization. An element side length of 1cm requires 3.6 billion elements if no symmetry conditions are applied. The loads applied to the section are section forces coming from a global beam model of the Bridge. The optimization is density based and solves the minimum compliance problem. A minimum of restrictions are applied. Single isotropic material is used.

The goal is to identify new and innovative, but at the same time constructible and economically reasonable solutions to be implemented into the design of future cable supported bridges.

106 Structural sizing optimization capabilities at AIRBUS

Stéphane Grihon

Structural sizing optimization at Airbus leans on different approaches depending on the needs. Two main solutions have been defined, mainly for questions of performance and deployment. A rapid solution (PRESTO) has been developed based on a pure discrete algorithm to perform parametric trade-off studies in early design stages. The structure optimization process has been simplified in such a way that it is as quick as possible. This is the right solution to be used by non-expert users in early overall aircraft studies. It exploits large databases and surrogate models in a Big Data mindset.
A more advanced solution (ACO-AMO) has been developed to support later design stages and more detailed optimization. It uses a standard continuous optimization approach based on gradient information and state of the art mathematical programming algorithms. A second step allows performing a discrete ply-by-ply optimization for composite covers using an optimization heuristic (ant colony paradigm). This is the right technology to address advanced structure optimization and to be included in MDO processes.
Both methods are under integration in a single platform (SOFIA) to provide adequate sizing optimization services for the relevant components (e.g. wing, fuselage) and design stages. A status will be made in this paper on the technologies used in the different tools, the applications performed and the current and future research and development axes especially in the effort to merge solutions or to integrate them in multidisciplinary processes.

107 Producing smart Pareto sets for multi-objective topology optimization problems

David Munk, Gareth Vio, Grant Steven

To date the design of structures via topology optimization methods has mainly focused on single-objective problems. However, real-world design problems usually involve several different objectives, most of which counteract each other. Therefore, designers typically seek a set of Pareto optimal solutions, a solution for which no other solution is better in all objectives, which capture the trade-off between these objectives. This set is known as a smart Pareto set. Currently, only the weighted sums method has been used for generating Pareto fronts with topology optimization methods. However, the weighted sums method is unable to produce evenly distributed smart Pareto sets. Furthermore, evenly distributed weights have been shown to not produce evenly spaced solutions. Therefore, the weighted sums method is not suitable for generating smart Pareto sets. Recently, the smart normal constraints method has been shown to be capable of directly generating smart Pareto sets. This work presents an updated smart normal constraint method, which is combined with a bi-directional evolutionary structural optimization algorithm for multi-objective topology optimization. The smart normal constraints method has been modified by further restricting the feasible design space for each optimization run such that dominant and redundant points are not found. The algorithm is tested on several different structural optimization problems. A number of different structural objectives are analyzed, namely compliance, dynamic and buckling objectives. Therefore, the method is shown to be capable of solving various types of multi-objective structural optimization problems. The goal of this work is to show that smart Pareto sets can be produced for complex topology optimization problems. Furthermore, this research hopes to highlight the gap in the literature of topology optimization for multi-objective problems.

108 Structural optimization of stiffened composite panels for highly flexible aircraft wings

Tobias Bach

For the development of new aircraft configurations, a wide range of technologies has to be taken into account. One technology that has shown to be beneficial is the highly flexible wing. In addition to aerodynamical parameters like wing span or profile height, the structural design concept has significant influence on the overall stiffness. The structural design concept is not only the type of stiffening element, but also the composite layup in wing skin and stringer objects. By using composite materials, the number of optimization parameters is significantly increased compared to metallic structures.

For structural design concept development of a highly flexible wing, a design and optimization environment has been developed, based on detailed finite element models (DFEM). The overall benefit of the flexibility is a reduction of the maximum loads. This can only be shown in a multidisciplinary process, so a gradient based optimization algorithm is incorporated in the optimization environment. DFEMs are used for several reasons. First, an accurate load distribution between skin and stringers is calculated as well as the loads on stringer objects. The partial derivative of the constraint gradient that covers the change of load on panel objects is calculated implicitly saving calculation time. Another advantage of the detailed models is the consideration of possible layup transitions in the stringer objects. They can occur due to design rules or manufacturing constraints in the design concept optimization. Their consideration increases the quality of the resulting panel mass and stiffness.

Using the DFEM based analysis environment, different design concepts are optimized on a local structural element level, representative for a long range aircraft wing. The demands of a highly flexible wing on the structure are considered. The design concept showing the best combination of mass and stiffness is then used to optimize the aircraft wing that has to be made more flexible.

109 Robust Design Optimization of Vehicle and Adaptive Cruise Control Parameter Considering Fuel Efficiency

Hansu Kim, Yuho Song, Kunsoo Huh, Tae Hee Lee

In recent years, interest in autonomous vehicle has been increasing in the automobile industry and research on advanced driver assist system (ADAS), which is the previous stage of autonomous driving, is actively proceeded. ADAS includes adaptive cruise control (ACC), lane

keeping assist (LKA), autonomous emergency braking (AEB) and so on. Mainly research on ACC and application of real car have been proceeded.
In the past, the development of an ACC algorithm considering fuel efficiency and the development of an ACC system considering performances such as fuel efficiency, ride comfort and trackability have been carried out. In addition, research on vehicle and ACC parameter optimization considering fuel efficiency, ride comfort, trackability and safety have been carried out. However, in real world, vehicle sprung mass and center of gravity are changed due to the number of passengers, and there is a variation in vehicle parameters such as tire radius, tire spring constant and so on. Therefore, ACC should be designed considering uncertainty due to variation of vehicle parameters.
In this paper, robust design optimization of vehicle and ACC parameters considering uncertainty of vehicle parameters is carried out to guarantee robustness of performances such as fuel efficiency, ride comfort, trackability, and safety. Before performing the robust design optimization, vehicle parameters which have significant influence on the performances were analyzed through analysis of variance (ANOVA) and uncertainty quantification was performed by analyzing scatter information of vehicle parameters. Since numerous function calls of high fidelity model analysis are needed to perform optimization that kriging surrogate model which is a mathematical model that can replace high fidelity model is employed and performed robust design optimization by using constructed kriging surrogate model.

110 Simultaneous topology optimization of material density and anisotropy

Narindra Ranaivomiarana, François-Xavier Irisarri, Dimitri Bettebghor, Boris Desmorat

A matter of great concern for the aeronautic industry is the reduction of the weight of the structure. Thus, great research effort is placed in the development of new methodologies for mass minimization. On a conceptual design level, topology optimization is increasingly used to determine either the best shape of a given structural component or the best layout of structures. One step further to reduce weight is optimizing the material, i.e., designing the anisotropy behavior. Composite structure optimization is commonly employed in industry as parametric optimization: e.g. designers aim at finding the best layup of a laminate through gradient-based or heuristic optimizations.

The aim of the present work is to bridge the gap between topology optimization and composite optimization by developing an innovative method for simultaneous topology and anisotropy optimization of composite structures. For this purpose, a compliance minimization optimization problem is defined with maximal volume constraint. A relaxed density based method is used to optimize the topology, and the penalty scheme SIMP is employed to avoid intermediate densities. Elasticity tensor invariants by change of frame are set as anisotropy optimization parameters. The optimization problem is solved using the alternate directions algorithm. The numerical procedure iterates between finite element stress analysis with fixed optimization parameters and local minimizations at element level with fixed stress tensors. By using the polar method, optimality conditions at local level are expressed by explicit formulas. The proposed method is straightforward and efficient: the computing time is low and the convergence to a stationary point is guaranteed. Results show that optimal shapes depend on the material anisotropy. Sequential and simultaneous topology and anisotropy optimization are compared on 2D-dimensional test cases.

111 Robust design of multimodal piezoelectric transducers

Alberto Donoso, José Carlos Bellido

Piezo modal sensors/actuators are those piezoelectric transducers which isolate a specific eigenmode of a structure, but also remain insensitive to the rest, that is to say, they behave as ideal spatial filters for a driving frequency different to the target one. The problem of designing modal transducers for plates can be elegantly regarded as an optimization problem by shaping properly the polarity of piezoelectric layers, which takes exclusively -1 or 1 values in the optimum.

This work is intended to be a continuation of the previous one and the purpose is twofold indeed. Firstly, generalize the foregoing problem formulation in order to filter a set of desired eigenmodes (rather than one) among those belonging to a bigger set prescribed beforehand. Furthermore, it is also proved that this new problem -design of multimodal transducers- which clearly comprises the design of modal transducers as a particular case admits classical solution and it is unique. And secondly, apply the so-called robust approach to control feature size of both black and white phases, in this case, positive and negative polarity phases. The latter is especially interesting at the micro scale as the goal designs are more sensitive to uncertain manufacturing errors.

112 A modified extended finite element method applied to control interfaces and cracks

Franz-Joseph Barthold, Felix Ermen

This paper describes a modified extended finite element method (XFEM) approach, which is designed to ease the challenge of an analytical design sensitivity analysis in the framework of structural optimisation. This novel formulation, furthermore labelled YFEM, combines the well-known XFEM enhancement functions with a local sub-meshing strategy using standard finite elements. It deviates slightly from the XFEM path only at one significant point. Instead of using the classical sub-integration technique on cut elements, the sub-domains are treated as sub-elements. Thus, it allows to use already derived residual vectors as well as stiffness and pseudo load matrices on the sub-elements to assemble the desired information on cut elements using a static condensation technique derived from the enhanced Ansatz functions on the cut element. Therefore, tedious and error-prone re-work of already performed derivations and implementations are avoided. The strategy has been applied to sensitivity analysis of interface problems combining areas with different linear elastic material properties in [1].

The benefits of this modified approach are the flexibility to combine design modifications of the structure (background mesh) with modifications of the interfaces or cracks. Furthermore, non rectangular background meshes using linear and quadratic Ansatz functions can be integrated easily.

In this paper we will enhance the methodology to strong interfaces, i.e. cracks. Furthermore, we will compare the proposed approach with existing traditional XFEM strategies.

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113 Efficient High Resolution Topology Optimization using Beam Modeling

Eilam Amir, Oded Amir

Continuum topological designs often consist of beam-like members of various shapes and sizes. A Topology optimization approach based directly on beam modeling has the advantage of being economical compared to continuum based procedures. Thus, it can be utilized not only for optimizing standard load-bearing components, but also for generating high resolution non-periodic porous structures which are difficult to realize with continuum models. Unlike continuum-based approaches that typically deal with a periodic unit cell, in the proposed approach optimization is performed on the full domain without length scale separation, hence it can bridge the gap between the micro and macro levels.
The suggested scheme relies on a ground structure parametrization with alternating phases of shape and sizing/topology optimization. The ground structure is constructed of tapered beam members to enhance the design freedom. Linear constraints link nodes movement so that the discrete domain emulates successively the continuum environment. Sensitivities are formulated using the adjoint method and gradient based algorithms are utilized for solving the two problems phases.
Optimized layouts obtained in 2-D are projected onto a compatible continuum domain and compared to standard continuum-based solutions, as well as to continuum optimization of high resolution structures. For stiffness-to-weight problems, the suggested procedure leads to superior performance, alongside a significant reduction in the computational effort. For compliant mechanism problems, the beam modeling needs further improvements in order to facilitate creation of flexible hinges. For the high resolution case, encouraging results are obtained that demonstrate the capability of designing a non-periodic porous layout. This formulation can be further utilized as a foundation for developing efficient approaches for optimizing high resolution structures that can be realized by additive manufacturing technologies.

114 Improved sequential optimization and reliability assessment for reliability-based design optimization

Sang-Hyeon Choi, Ikjin Lee

The sequential optimization and reliability assessment (SORA), which is a decoupled reliability-based design optimization (RBDO) method, is generally more efficient than conventional double-loop RBDO methods but less efficient than single-loop approaches because of the most probable point (MPP) search in the reliability assessment loop of SORA. This study presents improved SORA (ISORA) which is a single-loop version of SORA to further improve its efficiency. Simplified reliability assessment is performed at each iteration instead of the reliability assessment loop of SORA. The optimum with higher reliability than the deterministic optimum is searched by moving the limit state function toward the safe region utilizing a design shift vector in SORA which is approximated using the concept of the mean value method in ISORA. ISORA is divided into ISORAx and ISORAu in this study, according to the space used to define the approximated design shift vector. ISORAu is more effective than ISORAx because it does not need to approximate MPP and design point whereas ISORAx needs to approximate them for non-normal random variables. Numerical study shows that ISORAu is the most effective among RBDO methods tested in this study in terms of efficiency, accuracy and robustness.

115 Topology Optimization of Crash Structures with the Hybrid Evolutionary Level Set Method

Mariusz Bujny, Nikola Aulig, Markus Olhofer, Fabian Duddeck

Topology optimization plays an important role in many engineering fields, including crashworthiness. In most of the crash topology optimization methods, very strong simplifications of the underlying problem are made and often heuristic approaches are used. This makes the optimality of the obtained topologies arguable and limits the applicability of those methods just to selected use cases. Presented in previous works of the authors, Evolutionary Level Set Method, enables to solve the optimization problem directly, based exclusively on nonlinear, dynamic FE simulations of the crash problem. In spite of many advantages of the proposed method, including very good global search properties in highly nonlinear and noisy optimization landscapes and flexibility with respect to the use of different objectives and constraints, the computational costs are still very high. This can be to some extent mitigated through parallelization of the computations, which can be done very efficiently for Evolutionary Algorithms. Nevertheless, a further reduction of computational costs is inevitable. A hybridization of Evolutionary Algorithms with existing methods for crash topology optimization is one of the potential solutions of this problem. In this paper, a method taking advantage of the global search properties of Evolution Strategies enhanced with a local search based on a gradient information from the local Equivalent Static Loads Method is presented. To evaluate the proposed approach, a two-dimensional transverse bending crash case is considered. The performance of the proposed method for different objectives is compared with the standard Evolution Strategy. The results show that, an improvement in terms of convergence speed and performance of the obtained designs by the utilisation of predicted gradients in hybrid algorithms is possible. Thanks to the generality of the method, the approach can be further extended by introducing other estimated local gradients.

117 Optimal modular design of jacket structures for offshore wind turbines

Mathias Stolpe, Kasper Sandal

An optimal design approach is proposed to minimize material and manufacturing costs of frame structures for offshore applications. The discrete design variables are chosen from catalogues of values and several variables are assigned to each part of the structure. The design parametrization allows for structures consisting of modules of predefined geometries, sizes, and materials and the approach is useful for both conceptual and preliminary optimal design of structures. The overall purpose is to develop an approach which proposes designs suitable for mass-production.

The main application is optimal design of jacket support structures for offshore wind turbines at large water depths. The objective is to design jackets with modules of predefined outer (height and widths) and inner dimensions (thickness and diameters of members). The modules consist of legs connected by X-braces. The modules are stacked on top of each other to form a jacket. The module catalogues give the possibility to adjust the height of the jacket for the varying water depths in a wind farm.

The optimal design problem includes requirements on strength, stiffness, fatigue, and frequency properties. Timoschenko beam elements are used for the structural analysis and the sensitivity analysis is analytical. The main issue is the size of the catalogues from which the modules should be chosen. These catalogues are in general large for the considered applications. This difficulty is resolved by constraints on the geometry of the structure which are necessary to satisfy requirements on validity of the design standards and production techniques.

The problems are modelled as mixed 0–1 nonlinear problems with nonconvex continuous relaxations. Algorithms based on the concept of Outer Approximation are developed and implemented to find optimized designs. The approach is illustrated by optimal design of several offshore jacket support structures with different types of modularizations.

118 On a flexible overhang constraint in Topology Optimization for Additive Manufacturing

Alain Garaigordobil, Rubén Ansola, Estrella Veguería

This work falls within the scope of topology optimization procedures and additive manufacturing technologies. Due to the potential and fast spread of additive manufacturing technologies and their manufacturing freedom and potential, the integration of both technologies has become a highly demanded and highly competitive field of research. Hitherto there are many different investigators, universities and industries working for a proper engagement of the both technologies, additive manufacturing processes and topology optimization.

The need of a correct integration is due to pursuit of reducing the sacrificial material of the scaffold structures introduced in additive manufacturing to deal with the overhang problems. Lately different approaches are being proposed, every of them being jet nonmature, but demonstrating the importance of this field of research.

Until now, the proposed methods work with a design-process-guided value for the overhang constraint, not allowing the designer to loose or tightening the constraint value. This way, the designer can only obtain one single result for a same overhang restriction.

This paper introduces a novel approach that allows tightening or loosening the overhang constraint, generating more constrained or freer designs, which will directly influence on the number of scaffold structures in the final design. Here the designer will also be capable of controlling the complexity of the final structure as well as control, in a basic level, the manufacturing costs and the usage of sacrificial material. The designer may need to introduce scaffold structure for a concrete overhang value, then, this approach offers that capability.

The method is based on image processing algorithms and differently to what is been proposed to this moment, it introduces the overhang as a constraint in a multiple constrain topology optimization problem. One can work with distinct overhanging angles and many different overhang restriction values for each.

119 A topology optimization scheme for crash structures using Topological Derivatives

Katrin Weider, Axel Schumacher

In this contribution, a topology optimization scheme considering crash loaded structures is presented. Basis is a micro-scale calculation of the Topological Derivative (TD), which is the sensitivity of the objective functional for the introduction of an infinitesimal hole into the design space. The optimization of a macro-scale mechanical problem is done with a level-set method, using the micro-scale results.

In the micro-scale calculation, a meta-model of the TD is generated. According to [1], a microcell Finite Element model with a hole is loaded under various combinations of perpendicular stresses. Numerical integration is used for the calculation of the TD. This provides the sample points for the meta-model, which is depending on the objective functional and can be used for arbitrary loadcases.

During the optimization with the level-set method, the volume of the design space is reduced stepwise. Based on the Finite Element Analysis result of the mechanical initial value problem, the nodal sensitivities are taken from the meta-model of the micro-scale calculation. As crashs are time dependent, a time-modelling scheme is necessary. Furthermore, a linear projection scheme allows arbitrary meshes with smooth boundaries of the design space for the crash calculation and applies the sensitivies to a regular mesh of the whole design space. This implicitly gives the space for the reintruduction of former deleted areas. The level-set is then calculated and the isolines border the new structure for the next optimization step.

This optimization scheme will be illustrated with an academic example, which provides the differences to the linear static topology optimization and shows the effects of scaled loads on the structure.

[1] K. Weider and A. Schumacher, On the calculation of Topological Derivatives considering an exemplary nonlinear material model, PAMM, Vol. 16(1), 717-718 (2016).

120 Numerical artefacts in topology optimization approaches involving decoupled analysis and design discretizations

Deepak Gupta, Matthijs Langelaar, Fred van Keulen

Traditional topology optimization (TO) uses an element-wise constant density distribution. Thus, the structural design resolution is restricted by that of the finite element (FE) analysis

mesh. Multiresolution topology optimization (MTO) schemes decouple the design and analysis domains, such that a high-resolution design representation can be achieved at low analysis costs. In MTO, each FE is divided into a large number of density-cells (voxels) allowing a finer design description compared to a traditional FE-mesh-based design field.
Even worse than in well-known checkerboarding, MTO formulations can generate completely disconnected material patches, that still show significant stiffness in FE analysis. In our study, we show that this leads to highly unrealistic TO designs. Use of shape functions with high polynomial degree or using spatial filtering can help to reduce these artefacts. However, in the context of TO, it is not always viable to use high shape function orders, since it significantly increases the analysis cost. Secondly, filtering leads to smooth but gray boundary regions which are not desired for the fine structural features pursued by MTO.
Our aim is to understand and explain these artificially stiff patterns and to subsequently define effective countermeasures. In this contribution, we present parameter studies on the influence of both, polynomial degree and filter radius, on various test geometries and load-cases. From these tests, we conclude that the continuous shape functions used in MTO are incapable of accurately modeling the discontinuous displacement fields that should arise at the disconnected material patches within elements. Even for an approximate representation of such boundaries, very high shape function orders are needed. With such configurations, the advantage of MTO over traditional TO could be lost. We also demonstrate instances where even the use of traditional filters cannot eliminate the artificially stiff zones.

121 Optimal design of robust piezoelectric unimorph microgripper under large displacement

David Ruiz, Ole Sigmund

Piezoelectric grippers are widely used in the industrial world especially in the electronics field, where these devices perform the pick-and-place task for the positioning of electronic components.

This work presents a procedure based on the topology optimization method to design piezoelectric microgrippers, maximizing the displacement at the jaws.
The fabrication at the microscale leads us to overcome an important issue: the difficulty of manufacturing symmetrical laminates. The non-symmetric laminate produces a bending in the gripper that spoils its behaviour and needs to be suppressed. The suppression of this out-of-plane deformation is the main novelty of this work. The in-plane displacement of the gripper is modelled by using a geometrically non-linear model. In addition a robust formulation approach has been implemented in order to control the length scale in the structure.

The optimization problem proposed involves two variables that are optimized simultaneously, the topology of the host structure and the polarization profile of the electrode film.

122 Optimization of extradosed concrete bridges

Alberto Martins, Luís Simões, João Negrão

Extradosed bridges combine the main elements of both a prestressed box girder bridge (PBG) and a cable-stayed bridge. With their shallow cable-stays and stiff decks they represent an economic alternative to PBG bridges and cable-stayed bridges for main spans of 100 to 200 m. Their structural behavior combines the concepts of cable suspension and bending of the high stiffness box girder. The extradosed cable-stays introduce a highly effective prestress on the box girder which enhances its structural efficiency.

The use of optimization techniques in the design of large and complex structures like extradosed bridges naturally arises as an efficient way to compute the two sets of prestressing forces (box girder and cable-stays) and the cross-sectional dimensions of the tower and girder, aiming at reducing the material costs and thus obtaining economical and structurally efficient solutions.

The current research work is a development of previous research works by the authors concerning the optimization of concrete cable-stayed bridges. In this work a numerical model for the design of extradosed concrete bridges was developed. The structural analysis includes all the actions and relevant effects, namely, the construction stages, the time-dependent effects and the geometrical nonlinearities. The discrete direct method is used for sensitivity analysis. The design of extradosed concrete bridges is formulated as a multi-objective optimization problem with objectives of minimum cost, minimum deflections and stresses and a Pareto solution is sought. An entropy-based approach is used to find the minimax solution through the minimization of a convex scalar function. The design variables considered are the extradosed cable areas and prestressing forces, the deck prestressing forces and tendon areas and the towers and deck cross-sections.

The features and applicability of the proposed method are demonstrated by a numerical example concerning the optimization of a real sized extrad

123 Identification of input sound pressure level in hammering test based on adjoint variable and finite element methods

Eiki Matsuoka, Takahiko Kurahashi

Conventionally, if the nondestructive testing is carried out to investigate the reinforcement bar arrangement, methods using the electromagnetic wave radar and the electromagnetic induction are frequently employed in Japan. However, it is said that the measurement error for the investigation is not small, and it appears that it is necessary to improve the investigation system of the reinforcement bar arrangement. On the other hand, the hammering test is often carried out to investigate the cavity existence in concrete. It is known that this method is employed based on sense by experience for each investigators. Therefore, the improvement of the method of the hammering test is recently carried out by several researchers. It appears that if the measurement accuracy of the hammering test increases comparing to the conventional methods, there is possibility that the test can be easily and reasonably carried out. Therefore, we focus on the hammering test system.

In the hammering test, the sound pressure propagate in the target structure, and the evaluation of the cavity existence is carried out based on the frequency of the sound pressure. However, the input sound pressure level is also unknown value and it is necessary to obtain this value before the hammering test in order to investigate the defect size and position. Therefore, in this study, the numerical study for input signal identification is carried out based on the finite element and the adjoint variable methods.

125 Surrogate modeling in the design optimization of structures with discontinuous responses with respect to the design variables - A new approach

Carlo Boursier Niutta, Erich Josef Wehrle, Fabian Duddeck, Giovanni Belingardi

Computational technology advances have resulted in the reduction of computational effort for crashworthiness analysis, hence enabling structural design optimization. Surrogate modeling has been shown to further reduce computational effort as well as smoothing noisy responses. Crashworthiness optimization problems are, though, ill-posed as they include nonlinear, non-continuous, noisy responses. Violating the Hadamard conditions for well-posed problems, the applicability of gradient-based algorithms is limited.

Here, discontinuities in the responses with respect to the design variables will be handled that result in large changes in the system functions with only small changes in the design variables using a novel surrogate modeling technique. The applicability of typical global surrogate models is limited when critical discontinuities are present. An efficient method has been developed here to identify the number of discontinuities and their position in the design domain. Previous works assume a said number of discontinuities; here though, the presence and possible number of discontinuities are not given a priori. These are identified by examining the relative difference in the response value of samples in immediate proximity of each other. Samples in the same continuous subdomain are clustered and a support vector machine for classification is exploited to locate discontinuities. Local approximations are used for the continuous subspaces between the discontinuities. Lastly, a surrogate-based design optimization is carried out.

Starting with a two-bar truss, demonstrating a snap-through discontinuity, the method is shown to account for such discontinuities. This is then integrated into an optimization framework. Further, a crash-absorbing tube is optimized that is impacted with an angle resulting in a noncontinuous design space: desired axial crushing and undesirable global buckling. After summarizing the results, advantages and possible limitations are discussed.

126 Interpretation of 3D Two-Scale Optimization Results

Bich Ngoc Vu, Thomas Guess, Fabian Wein, Michael Stingl

We consider a two-scale material optimization approach in linear elasticity using homogenized base cells as introduced in [1].

We aim to realize the full workflow from optimization towards printing by additive manufacturing technologies. This encompasses the classification, selection and design of a suitable three-dimensional base cell with respect to manufacturing constraints. The design variables model the local orthogonal stiffnesses of the base cell. In particular we suggest structures with strong differences in these orthogonal stiffnesses and elaborate reasons for this choice.

In order to obtain a continuously connected and manufacturable lattice structure, we interpret the two-scale optimization result in a post-processing step and generate a ready-to-print surface description of the lattice structure. This result then provides the base for a numerical validation of the obtained macroscopic design.

[1] M. P. Bendsøe, N. Kikuchi, Generating Optimal Topologies in Structural Design using a Homogenization Method, Computer Methods in Applied Mechanics and Engineering 71, 197-224, 1988.

127 Using Gaussian Process to Enhance Support Vector Regression

Yi Zhang, Wen Yao, Xiaoqian Chen, Fred van Keulen

Support vector regression (SVR) is a common surrogate model for computationally expensive simulation. It is able to balance the model complexity and the error tolerance. Whether SVR interpolates the training samples is dependent on its parameters. For the nonlinear function approximation without noise, when SVR is not an interpolator, it is advisable to model the errors and and use them to compensate the prediction response. In this paper, the errors of SVR are modeled by using Gaussian process, and the final model response is obtained by the combination of SVR and the Gaussian process of the errors. The numerical experiments show the proposed method is able to further improve the prediction accuracy of SVR.

128 Temperature Constraint Formulations for Heat Conduction Topology Optimization

Danny Lohan, James Allison

In this paper an investigation of formulations for temperature constrained topology optimization is presented. This investigation is motivated by power electronics applications where the temperature requirements of several devices constrain the design of passive heat spreaders. Efficiently obtaining an accurate measure of temperature for use in density-based topology optimization is challenging. Enforcing point-wise distributed constraints increases the computational burden of the optimization, and utilizing global constraints often result in inaccurate constraint evaluations. Three maximum approximation functions are investigated as a means to improve the accuracy of the constraint evaluation. The soft maximum function is found to outperform the p-norm and is used in demonstrative examples. The accuracy of the soft maximum function is tested with both global and regional constraint implementations.

129 Multicriterial optimization of geometrical and structural properties of the basic module for a single-branch Truss-Z structure

Machi Zawidzki, Lukas Jankowski

Truss-Z (TZ) is an Extremely Modular System (EMS). EMSs allow for creation of structurally sound free-form structures, are comprised of as few types of modules as possible, and are not constrained by a regular tessellation of space. The objective of EMS is to create spatial structures in given environments connecting given terminals without self-intersections and obstacle-intersections. In EMS, the deployment and configuration difficulty is moved towards the module, which is relatively complex and whose assembly is not intuitive. As a result, EMS requires intensive computation for assembling its desired free-form geometrical configuration, while its advantage is the economization of construction and reconfiguration by extreme modularization and mass prefabrication.

TZ is a skeletal modular system for creating free-form pedestrian ramps and ramp networks among any number of terminals in space. TZ structures are composed of four variations of a single basic module (TZM) subjected to affine transformations (mirror reflection and rotation). The previous research on TZ focused on global discrete optimization of the spatial configuration of the modules. This contribution presents the first attempt at structural optimization of the TZM for a single-branch TZ. Two qualitatively different objectives have to be taken into account: (1) the capability of TZM to create free-form shapes and (2) the structural performance of the resulting TZ. The former is quantified in terms of the ability of the considered TZ to follow closely a reference path in space. The latter objective relies on the typical structural criterion of von Mises effective stress under given static load applied to the worst case of all 256 unique 5-module configurations. The result is a multicriteria optimization problem, where the Pareto front provides the means to strike the optimal balance between the geometric and structural assessment criteria.

130 Some New Eigenvalue Criteria for Structural Optimization Under Harmonic Loading

Bo Ping Wang

In structural dynamics, it is well known that resonance frequencies in forced harmonic response of an undamped structure are related to the eigenvalue for free vibration problem. These resonance frequencies are the peaks in the frequency response plots. In a recent paper, it is shown that the frequencies for the valleys (lowest points in vibration amplitude) in the frequency response plot can also be computed by solving eigenvalue problems associated with the forced harmonic response of the system. When the minimum response is zero, the corresponding frequencies are the well-known antiresonsnt frequencies. Otherwise, these are minimum response frequency between two resonances. Using the eigenvalue formulation, the sensitivities of the antiresonant or minimum response frequency can be readily computed using eigenvalue sensitivity results for general non-symmetrical matrices. In this paper, these new eigenvalues will be used in the objective or constraints in structural optimization under harmonic loading. This is achieved by tailoring the structure so that minimum response or antiresonsnt frequencyoccurs at the specified forcing frequency.Detailed formulations will be presented in the paper. Several beam problem will be use to illustrate the general formulations.

131 Topology optimization for unifying deposit thickness in electroplating process

Naoko Ishizuka, Takayuki Yamada, Shinji Nishiwaki

Uniformity of deposited thickness in electroplating processes is vital to the realization of desirable surface qualities in many products. The thickness distribution of deposits is affected by numerous factors, such as the arrangement and shapes of auxiliary cathodes, anodes, and shields as well as the detailed configuration of the electroplating process. Deposit thickness reflects the amount of ions transported from anodes to cathodes, particularly to the object being plated, although auxiliary cathodes are sometimes placed to prevent excess plating in certain areas of the product, as are shields that impede current flow.

This study presents a topology optimization method for achieving uniform deposition thickness, applied to the design of the shields, auxiliary cathodes and anodes placed in an electroplating bath. The proposed method is based on the level set method and the FEM is used to analyze the electrochemical field. The shapes and arrangement of shields in an electrolyte are expressed according to the distribution of electric conductivity via a level set function, and the shapes and arrangement of anodes and auxiliary cathodes are expressed with respect to ion sources using other level set functions. The Kreisselmeier-Steinhauser function for the current density distribution on a cathode is employed as an objective function, since current density is nearly proportional to the thickness of the resulting electroplating. The magnitude of the current density on the cathode is used as a constraint to prevent its falling below a certain value, to avoid extended processing time that might result if the current density were excessively inhibited. Numerical examples are presented to confirm the utility of the proposed method and the results demonstrate that the proposed method can obtain appropriate shapes and arrangements of shields, auxiliary cathodes and anodes in a plating process to achieve a uniform deposition thickness.

132 Optimization of periodic cells for nonlinear response

Daniel Tortorelli, Mathias Wallin,, Niklas Ivarsson

We have developed programs for the design of unit cells that incorporate geometrically nonlinear kinematics and hyper elasticity. Formulations based on the Representative Volume Element (RVE) and homogenization are presented. Designs are obtained using topology optimization wherein the material indicator field which defines the physical domain is optimized. As per usual, the indicator field is convexified by the volume fraction field to enable gradient-based optimization, geometric restriction is used to generate well-posed optimization problems and penalization is used to generate binary, i.e. black-and-white designs. The goal of the optimizations are to design composites for maximum energy dissipation subject to constraints on mass, stiffness and material symmetry, e.g. that the composite exhibit orthotropic material response. The design, i.e. volume fraction field, is parameterized as elemental volume fractions, gradients are derived via the adjoint method, the response and gradients are computed via the finite element method and the Method of Moving Asymptotes (MMA) is used to solve the optimization problems. Two-dimensional design examples are used to illustrate the differences between the RVE and homogenization theories.

133 Topology optimization of viscoelastic composite materials for macrostructures

Qiming Liu, Xiaodong Huang

Based on bi-directional evolutionary structural optimization (BESO) method, an algorithm of material microstructure topology optimization is proposed for damping characteristics of the macrostructure. This optimization algorithm aims to obtain the optimal topologies of the material microstructures so that the resulting structure with given weight fraction has optimal damping characteristics. The design concept of this scheme is essentially a two-scale design which takes the effective material properties at micro-scale level and the macroscopic performance at macro-scale level into design consideration. Viscoelastic material which has properties of both viscosity and elasticity is designed in this optimization scheme for the damping of the macrostructure. An additional frequency constraint is applied so that the resulting macrostructure to have prescribed natural frequencies. The microstructures of the material are represented by periodic unit cells (PUCs) and the effective properties of the material microstructures are homogenized and integrated into the finite element analysis of the macroscopic structures. The sensitivity analysis with the variation of design variables is conducted for iteratively updating the topologies in the design domain synchronously following the BESO process. Numerical examples are presented to demonstrate the validity of this optimization algorithm.

134 Level set-based topology optimization for multi-material problems

Takayuki Yamada, Naoki Kishimoto, Kazuhiro Izui, Shinji Nishiwaki

A number of structural optimization methods for multi-material problems have recently been proposed, in which the methods are constructed based on the density approach or a level set-based shape optimization method. This work presents a topology optimization method for multi-material problems using a multi-material level set method. First, the multi-material problems are formulated using level set boundary expressions. Next, a topology optimization algorithm is constructed using a reaction-diffusion equation and the finite element method. Finally, several numerical examples are provided to confirm validity of the proposed topology optimization method.

135 Optimization design of smart reversible diaphragm using shape memory polymer

Qingsheng Yang, Ran Tao

As a new intelligent actuating material, shape memory polymer (SMP) can prone to deformation under high temperature conditions and can maintain the temporary deformation after unloading under low temperature condition. As the temperature increases again, SMP will recover its original shape. Currently, SMP has been widely used in the field of aerospace, biomedical and 3D printing. In order to solve the problem of cannot be reused on the traditional diaphragm, a novel reversible diaphragm by using shape memory polymer is developed in this work. The overturning and recovery behavior of the SMP diaphragm are analyzed by using nonlinear finite element method to exhibit the advantage of the diaphragms. The effect of the thickness, height, radius of the diaphragm and temperature on overturning performance is investigated. Then an optimization model is established with the minimum pressure required for completing overturning deformation as target function and the thickness, height and radius as variables of design. Optimized SMP diaphragm is obtained under the critical pressure constraints. This research can contribute to the design and application of novel SMP diaphragm.

136 A simple approach to deal with zero densities in topology optimisation

Kazem Ghabraie

Topology optimisation involves improving a design by redistributing material. This includes creating new voids and filling existing voids. Rather than completely removing the material by using zero density (ρ_min $= 0$) in voids, however, a very weak material with a small positive density (ρ_min $= \varepsilon > 0$) is typically used to model voids. This approach effectively converts the topology optimisation problem to a sizing optimisation problem.

Despite its simplicity and generally acceptable results, this approach can impose some difficulties particularly in terms of selecting the appropriate value of ε. The weak material should be weak enough to validate the approximation of void areas, but on the other hand, using a very weak material can result in ill-conditioning of the stiffness matrix. Further complications can arise, for example in non-linear problems where weak elements cause numerical instabilities in the solution procedure (see e.g. Buhl et al 2000 and Lahuerta et al 2013).

By studying the mechanical responses of structures when $\varepsilon \to 0$, this paper presents a simple approach to use arbitrarily weak material properties in void areas. This approach would effectively allow us to actually remove the void areas from the mesh in a range of problems and avoid the above-mentioned complexities.

Buhl T, Pedersen CB, Sigmund O (2000) Stiffness design of geometrically nonlinear structures using topology optimization. Structural and Multidisciplinary Optimization 19(2):93104.

Lahuerta RD, Simoes ET, Campello EMB, Pimenta PM, Silva ECN (2013) Towards the stabilization of the low density elements in topology optimization with large deformation. Computational Mechanics 52(4):779797.

137 Sizing Design of Microwave Metamaterial Absorber (MMA)

Kepeng Qiu, Ning Jia, Weihong Zhang

Metamaterials are characterized by negative effective permittivity and permeability. They can be designed for perfect wave absorption by impendence matching. The matched permittivity and permeability can be achieved by adjusting the size parameters of MMA. In the practical application, various microwave metamaterial absorbers were developed to pursue the characteristics of multi-band, wide bandwidth, polarization-insensitivity and wide incidence angle. In our work, we combined the design principle with optimization method to further improve the absorption property of microwave metamaterial absorbers. By analyzing the influence of the geometry parameters on absorbing property, we found that the absorption bandwidth could be broadened further by optimizing the size parameters of MMA. First, the geometric parameters of the substrate such as side length and width affect the absorption bandwidth. Especially, the resistance and capacitance loaded on the substrate by unit cell have a great impact on the bandwidth because the resistance can enhance the consuming ability of circuit. The capacitance can enhance the circuits storage capacity. And the electromagnetic energy in the free space can be transformed into the electric energy of the circuit and then consumed. In addition, the gap width, the length and width of split, the width between inner circuit and outer circuit have a little influence on the bandwidth. However, the bandwidth fluctuates significantly when the gap width changes within a certain range. Therefore, it is necessary to consider the size parameters as the design variables in this optimization problem. Finally, the new combination of the unit cell sizes is obtained by maximizing the absorption bandwidth of the MMA by the genetic algorithm. The optimal results demonstrated the multifunctional absorption characteristics of microwave metamaterial absorbers.

140 Topology Optimization of Density Type for Linear Elastic Body Using the Second Derivative of KS function with Respect to the von Mises Stress

Wares Chancharoen, Hideyuki Azegami

This paper shows a Newton method to solve topology optimization problems of density type for linear elastic bodies to minimize the maximum von Mises stress. In order to avoid the non-differentiability of the maximum von Mises stress coming from the locality including the singularity and the jumping property, we use the Kreisselmeier-Steinhauser (KS) function as a cost function. With respect to the limitation of the range of density, we define a function with no restriction on the range defined in the domain of a linear elastic body as a design variable and assume that the density is given by a sigmoid function of the function of the design variable. To find the optimum density, an iterative scheme based on the Newton method, which we call H1 Newton method, using the second derivative of the cost function together with the H1 gradient method using the first derivative of the cost function. The effectiveness of the H1 Newton method is demonstrated by numerical results for a L-shaped linear elastic body model. A computer program is written by the language of FreeFem++. The numerical results show that the proposed H1 Newton method is faster than the H1 gradient method. Moreover, superiority in performance of the obtained structures according to stress-based optimization also can be found by the H1 Newton method.

141 Topological structure design for microwave applications using a new interpolation scheme

Hyundo Shin, Jeonghoon Yoo

In this study, we propose a structural optimization method based on the phase field method to design a patch antenna. Design of the metallic structure based on the finite element analysis (FEA) at microwave bands generally requires highly refined mesh or adaptive mesh generation to deal with the skin effect. The method intends to take the skin effect into account and to derive the structural configuration of the metallic patch portion.
The objective function is set to minimize the return loss of the power input port of the antenna system at a target frequency. We propose an artificial material called as an artificial PEC with a new interpolation scheme. The material property is determined based on the relative permittivity from the complex refractive index to represent the conductive region at microwave bands. The interpolation scheme is suggested based on the sigmoid function [1], which attenuates sharp variation of the design sensitivity caused by the large difference between the conductive material and the void region. To determine the clear boundary by

eliminating the gray scale region of the derived optimal model, the adaptive meshing scheme is performed with a parametric study by varying the contour level of the phase field parameter in the intermediate region. The design process was performed by using Matlab programming associated with the commercial FEA package COMSOL multiphysics 3.5a.

[1] Yin X, Goudriaan J, Lantinga EA, Vos J, Spiertz HJ (2003) A flexible sigmoid function of determinate growth. Ann Bot 91: 361-371.

142 Parallel multi-objective expected improvement criteria for expensive multi-objective optimization

Dawei Zhan, Jiachang Qian, Jun Liu, Yuansheng Cheng

Many engineering optimization problems involve multiple objectives and sometimes these objectives are very computationally expensive. The multi-objective efficient global optimization (EGO) algorithm which uses a multi-objective expected improvement (EI) function as the infill criterion, is an efficient approach to solve these expensive multi-objective optimization problems. However, the state-of-the-art multi-objective EI criteria are very expensive to compute when the number of objectives is higher than two, thus are not practical to use in real-world problems. In earlier work, the authors have proposed three cheap-to-calculate and yet efficient multi-objective EI criteria for the expensive multi-objective optimization. In this work, these three multi-objective EI criteria are extended for parallel computing to further accelerate the search process of the multi-objective EGO algorithm. The approach selects the first candidate at the maximum of a multi-objective EI criterion, and then multiplies the initial multi-objective EI landscape by the influence function of the first candidate. The influence function is designed to simulate the effect the first candidate will have on the landscape of the multi-objective EI criterion. Then the second candidate can be selected at the maximum of the approximated multi-objective EI criterion. As the process goes on, a desired number of candidates can be generated in a single optimization iteration. The proposed parallel multi-objective EI criteria have shown significant improvements over the single-point multi-objective EI criteria on the selected test instances. The results indicate that the proposed parallel multi-objective EI criteria can speed up the search process of the multi-objective EGO algorithm when parallel computing is available.

143 Topology optimization method for the laminate structure using the layerwise theory

Jong Wook Lee, Gil Ho Yoon

In this research, a new topology optimization method is developed for a laminate composite structure using the layerwise theory. As laminate composite structures are consisted of thin layers, classical plate and shell theories cannot be applied for structural analysis. However, there are the computational difficulties. To overcome it, the layerwise theory assuming the continuous displacements along thickness with one piecewise continuous function was developed. In the present study, a new topology optimization based on the well-developed layerwise theory is formulated and the effect of the composite laminate on optimal layouts is observed. In the sensitivity analysis, the influence of the dependency of the strain-displacement matrix with respect to the design variables should be considered. By solving some benchmark examples, the validation of the present study is demonstrate and some effects of the angle each ply and the number of plies are presented in this research.

144 New advances of manufacturing and interface-related topology optimization problems with implicit geometrical description

Zhan Kang, Pai Liu, Yaguang Wang, Yiqiang Wang

In topology optimization of multi-material or multi-component structures, certain geometrical constraints and interface behaviors are often of great importance to ensure the manufacturability or integrity of the structures. In this paper, we present some of our recent developments on the study of manufacturing and interface-related topology optimization problems in the level set function-based framework. The level set, as an implicit geometrical model, offers a natural description of shape and topology evolution. We extend the level set model to geometrical modeling of multi-material and multi-component structures. We propose a unified integral-form constraint to avoid overlaps, and to control the distances among the embedded objects. The constraint has an explicit form, facilitating their sensitivity analysis with respect to shape variations, and are applicable to the cases with many embedded components of arbitrary shapes. An integral-form casting constraint is also given to ensure the manufacturability of cast parts in topology optimization. Using the geometrical information extracted from the level set functions, the material interfaces are treated with the cohesive zone model. The extended finite element method is further used to reflect the displacement discontinuity across the material interfaces, thus possible separation of the interfaces can be well captured in the topology optimization. We also propose a level set-based implicit description model for modeling geometrical uncertainties with certain spatial distribution characteristics. Such a model has been employed in robust topology optimization considering random manufacturing errors.

[1] Y. Wang, Z. Kang. International Journal for Numerical Methods in Engineering.

[2] P. Liu, Y. Luo, Z. Kang. Computer Methods in Applied Mechanics and Engineering.

[3] W. Zhang, Z. Kang. International Journal for Numerical Methods in Engineering.

145 Topology optimization considering the dynamic fatigue caused by fluctuating amplitude load

Seung Hyun Jeong, Jong Wook Lee, Gil Ho Yoon, Dong-Hoon Choi

A new layout optimization method is developed in this research to consider high cycle fatigue caused by fluctuating dynamic load. We use transient analysis to obtain stress time history, multiaxial cycle counting to extract effective stress cycles, and Miner's cumulative damage rule to calculate total fatigue damage at every spatial element. Although the fatigue is a very important property in design of mechanical components, it has rarely been considered in the topology optimization because the calculation of exact sensitivities of a transient system is very complex and time consuming. The key idea of this research to resolve the difficulties in sensitivity analysis is to use the pseudo-sensitivities by applying equivalent static load approach. In addition, as an aggregated fatigue constraint is very sensitive to the changes in stress value, a new scaling approach of the aggregated fatigue damage constraint is developed. To validate the usefulness of the developed approaches, we solved some benchmark topology optimization problems and found that the present method provides physically appropriate layouts with stable optimization convergence.

146 Designing Micro-structures with Negative Poisson's Ratio by Utilizing Topological Derivative in MMC Framework

Meisam Takalloozadeh, Gil Ho Yoon

The application of the negative Poissons ratio materials (auxetics) is growing rapidly in mechanical and bio-mechanical applications. Although this type of material was found in the nature, auxetics materials are designed and made for industrial application. The present study designs micro-structure layout to make auxetics materials by utilizing topology optimization in moving morphable components (MMC) framework and minimizing the Poissons ratio. The MMC framework explicitly described a topology through a finite number of components. The position and shape values of each component were defined as design variables. Since shapes of the components are defined explicitly, it is easy to establish a link between CAD and the obtained layout. The concept of mechanism topology optimization was utilized for finding optimum design. One of the most important advantages in compliant mechanisms is to be able to control the ratios between output and input displacements. Topological derivative was developed and used in MMC framework for sensitivity analysis. The obtained layout was made by additive manufacturing and was tested for its desired properties.

147 Shape Optimization for Bodies of Musical Instruments

Takuya Hayashi, Hideyuki Azegami

In this paper, we formulate a shape optimization problem for bodies of musical instruments such as acoustic guitars and violins, and show its numerical solution. A musical instrument is modeled as a boundary value problem of coupling partial differential equations for linear elastic body and sound pressure field surrounding the linear elastic body. The Sommerfeld radiation condition is employed on the outer boundary of the sound pressure field to approximate a finite field to an infinite field. A design variable is defined by a function denoting displacement of domain variation. An integration of sound power on the outer boundary of the sound pressure field and in a specified frequency range is chosen as an objective cost function. The volume of the linear elastic body is used as a constraint cost function. The shape derivative of the objective cost function is evaluated by the adjoint variable method. An iterative algorithm based on the H1 gradient method is applied to the solution of the shape optimization problem. To solve the boundary value problems for the state determination problem, the adjoint problem and H1 gradient method, the finite element method is employed. A computer program is developed by the authors originally. Numerical results gave monotonous increases in the integration of the sound power while satisfying the volume constraint.

148 Efficient Global Optimization Strategy Considering Expensive Constraints

Bin Yuan, Li Liu, Teng Long, RenHe Shi

This paper proposes a novel augmented Lagrange multiplier based efficient global optimization strategy (denoted as L-EGO) to solve black-box design optimization problems involving computationally expensive constraints. The original objective function, constraint functions, multipliers and exterior penalty function are integrated to construct an augmented objective function. By optimizing the expected improvement of the augmented objective function, the sample points are sequentially generated to refine the Kriging metamodel, and the Lagrange multiplier and penalty factor are updated during the iteration, which leads the optimization process converging to the feasible optimum efficiently. Two benchmark problems are used to test the proposed method via comparing with another metamodel-based optimization algorithm (i.e., CiMPS). The comparison results show that L-EGO outperforms CiMPS in terms of global convergence, efficiency, and robustness. Finally, L-EGO is applied to solve a practical all-electric GEO satellite multidisciplinary design optimization (MDO) problem, which involves seven expensive constraints. Compared with the initial design, the optimized solution reduces the total mass of the satellite by 7.1% and satisfies all the constraints, which demonstrates the effectiveness and practicality of the proposed L-EGO method.

149 Preliminary Study on Optimization of a Bulge Tool for Nuclear Fuel Manufacturing

Jae-Jun Lee, Young-Duk Sim, Nam-Gyu Park, Se-Ick Son, Jong-Sung Yoo

A nuclear fuel assembly, manufactured through several processes, is composed of a range of components. Guide thimbles and spacer grid sleeves, among others, are particularly important to maintain the integrity of fuel assembly, and they are connected through a bulge forming process. The purpose of the bulge process for fuel assembly is to connect guide thimbles to spacer grids. The connecting load between tubes is affected by bulge joint strength, and this strength depends on bulge design. While reaching to a specified load, bulge equipment endures high working loads during the working process, and a cracked tool can be seen sporadically. The equipment consists of a bulge tool and a taper pin, and the neck of the bulge tool is most susceptible to damage. A crack may appear in fuel assembly when the bulge tool is broken during the bulge process. The optimization of bulge equipment is difficult because the bulge process has geometric nonlinearity, boundary nonlinearity, and material nonlinearity. The work velocity of the bulge process for nuclear fuel manufacturing is relatively slower than general forming processes, but a stroke is very important. Therefore, nonlinear analysis should be required in the optimization process. In this research, the design of experiments using an orthogonal array and the finite element analyses are employed to determine the optimal shape and material. Design variables are the material and three types of local shapes of a bulge tool, and the level of the design variables is three. The objective of the optimal design is to reduce the maximum stress imposed on a bulge tool. The commercial software, ABAQUS, is utilized for nonlinear static analysis of the bulge process, and L9 orthogonal array is used for the optimization of the bulge tool.

150 On fast design of innovative hierarchical stiffened shells against imperfections

Kuo Tian, Bo Wang

Inspired by the hierarchical features of some bionics structures like dragonfly wings and glass sponges, we propose the innovative hierarchical stiffened shell from the point-of-view of increasing the hierarchies of grid-patterns. Differing from the traditional hierarchical stiffened shells, the innovative ones are composed of major and minor stiffeners with diverse grid-patterns. However, its post-buckling analysis and imperfection sensitivity analysis are too time-consuming. Therefore, it is crucial to develop an efficient equivalent model and optimization framework.
Since various buckling modes may occur in hierarchical stiffened shells, it is essential to establish a more flexible equivalent strategy than the traditional single equivalent strategy. Firstly, the Numerical-based Smeared Stiffener Method (NSSM) is derived. Based on the NSSM, a reasonable adaptive equivalent strategy is developed from the concept of hierarchy reduction. Its core idea is to self-adaptively decide which hierarchy of the structure should be equivalent according to the critical buckling mode rapidly predicted by NSSM. On basis of the proposed adaptive equivalent strategy, an effective grid-pattern optimization framework is proposed. Firstly, the RBF surrogate model is constructed based on the equivalent model. Then, the inner optimization is performed on the surrogate model using global optimization algorithm. Furthermore, the optimum result is validated with the corresponding exact detailed model simulation, and the relative percentage error is served as a convergence criterion, to decide whether the adding the exact detailed model result into original surrogate model to generate a new one. Until the relative percentage error converges, the entire optimization is finally completed. Finally, representative illustrative examples indicate that one hierarchical stiffened shell with closely-spaced major stiffeners and triangle gird sub-structure is competitive in resisting imperfections.

151 Orthotropic Material Orientation Optimization and Manufacturing in Composite Structures

Mario Petrovic, Tsuyoshi Nomura, Norio Tada, Takaaki Takahashi, Shinji Nishiwaki, Kazuhiro Izui

A method for optimizing orthotropic material orientation in a composite structure is presented. The complete process starting from the optimization of orthotropic material orientation, result postprocessing and formatting for manufacturing, and finally, the manufacturing of the composite structure is shown.
The optimization method uses Cartesian vector components of the orientation angle as the design variables. Compared to the Continuous Fiber Angle Optimization (CFAO), this method provides additional degrees of freedom and avoids problems with local minimums.
In addition, the 2π ambiguity is also avoided. Isoparametric shape functions are used to handle the point-wise quadratic constraints needed for the feasibility of the Cartesian parametrization. The regularization of function space is done by applying a Helmholtz PDE filter. The regularized Cartesian components are used to assemble an orientation vector field which rotates the material properties matrix of the orthotropic material. The obtained op-

timal orientation vector field is transformed into a scalar field by applying the coupled time dependent non-isotropic Helmholtz equation. The scalar field, indicating the distribution of the orthotropic material, can be tuned to improve manufacturability.
The optimization method is applied to a prototype inverter case model used in hybrid cars for voltage conversion. The inverter case requires heat flow control in order for the electronics to function in optimal temperature ranges. The low thermal conductivity core of the case is coated by a two phase orthotropic material where one phase has high thermal conductivity and the other low thermal conductivity. The orthotropic material orientation is optimized to direct heat towards heatsinks and away from sensitive electronics. Finally, the manufacturing of the optimal design is shown.

153 Optimal Design of a Suspension System for a wheelchair Based on a Compliant Mechanism

Masakazu Kobayashi

In recent years, a compliant mechanism has been paid to attention as a new mechanism to replace a traditional rigid link mechanism. A compliant mechanism achieves a specified motion by deforming the structure elastically instead of relying on traditional joint movements. Compared to traditional mechanisms, compliant mechanisms have several merits due to their monolithic structure without joints. Thus, the use of compliant mechanisms in mechanical products, medical instruments and MEMS can be expected to increase. In this research, we apply a compliant mechanism to a suspension system of a wheelchair. Most wheelchairs except some expensive ones don't have a suspension system and only rely on tires for absorbing vibration and shock from a road. Since a compliant suspension consists of fewer parts than a traditional suspension and can be potentially integrated into a frame of a wheelchair, a compliant suspension can be added to a wheelchair at low cost. The proposed suspension system is a monolithic structure that acts as suspensions of a front caster wheel and a rear wheel and a single shock absorber is shared between front and rear suspensions. In this research, we design the system using the two-stage design method consisting of topology and shape optimization and confirm its effectiveness.

154 RBF-based High Dimensional Model Representation Method Using Proportional Sampling Strategy

Xin Li, Teng Long, G.Gary Wang, Kambiz Haji Hajikolaei, Renhe Shi

To effectively tackling high dimensional, expensive, black-box (HEB) problems, this paper proposes a modified radial basis function based high dimensional model representation method using proportional sampling strategy (denoted as RBF-HDMR-PS). Different from the standard RBF-HDMR, the proposed RBF-HDMR-PS sequentially adds first order sample points with a predetermined proportion coefficient to effectively construct each component RBF, which avoids the stochastic influence of random sampling process in RBF-HDMR. The proposed RBF-HDMR-PS using different proportion coefficients is tested through two benchmark numerical problems with highly nonlinear first order components for comparing with RBF-HDMR. A best proportion coefficient is chosen and integrated into RBF-HDMR-PS.

The comparison results show that RBF-HDMR-PS outperforms RBF-HDMR in terms of approximation accuracy.

155 A new topology optimization method for non-matching elements using variable node element

Gil Ho Yoon, Chung Hee Yoon

In topology optimization literature, the parameterization of design is commonly carried out on matching mesh. These formulations, however, suffer from some difficultness if we optimize structures including non-matching mesh. A problem is that additional mesh refinement process is required to analyze and perform topology optimization if structures to design include non-matching meshes, which affects analysis result and optimization result significantly. Thus, we examine the use of variable node element to reduce the influence of mesh geometry on topology optimization solutions. More specifically, we state and perform the topology optimization problem containing non-match meshes and using variable node elements. Furthermore, we analyze results of some examples to find influences of mesh dependence and topology optimization techniques such as filtering.

156 A Study of Lattice Structures Based on Topology Optimization and Additive Manufacturing

Takafumi Nishizu, Tomoya Tanitsugu, Akihiro Takezawa, Kazuo Yonekura, Mitsuru Kitamura

Lattice structures are generally used inside the structural member in order to reduce the weight. The shape of the lattice structure relates on a structural performance. One advantage of the lattice structures is that we do not need to change the whole structural shape when we replace the solid part of a component with the lattice structures. Recently, these structures have attracted attention as advanced composite material with new mechanical characteristics. Since the weight is one of the most attractive advantages of lattice structures, it is important to design a high performance lattice shape with low weight.
However, design and production on control performance of micro lattice structure are difficult. Thus, we propose a method for designing and producing micro lattice structures. We use a topology optimization method for a designing methodology. Topology optimization is an effective method in designing high performance lattice structure because topology optimization allows us to change the topology and to design a complicated shape. We use a metal additive manufacturing (AM) machine for producing the optimal lattice structures. AM allows us to produce a complicated structure which removal and forming manufacturing cannot produce.
We use a bulk modulus as the objective function since it is important mechanical characteristic in design. In this research, we use a homogenization method to compute the bulk modulus. Structures produced by AM need holes so that internal metal powder can be removed. Hence, we defined the design domain in order that the optimal structure becomes open cell structure. Then, high bulk modulus shapes were derived using topology optimization. The lattice structures were produced by metal AM machine with Electron Beam Melting (EBM) after being modified for production.

We measure the bulk modulus of lattice structure by strength test and check performance with result of numerical analysis.

157 Optimization of non-linear structures using the tangent stiffness

Mathias Wallin, Niklas Ivarsson, Daniel Tortorelli

In this paper stiffness optimization of geometrically non-linear elastic structures is investigated. Due to the non-linearity, several possible stiffness measures can be identifed and in this work the conventional compliance, i.e. end displacement stiffness is compared to the end-tangent stiffness. The optimization problem is solved by the method of moving asymptotes and the sensivities are calculated using the adjoint method. The sensitivity analysis for the end-tangent objective requires the third order derivative of the strain energy an nonetheless efficient formulation for calculating the sensitivity can be obtained. Loss of convergence due to large deformations which results in inverted and highly distrorted elements in void regions is handled by introducing a fictitious strain energy such that small strain linear elasticity is approached in the void regions. The problem is regularized using a global Helmholtz type filter. The examples show that designs for low load levels coincide whereas the designs for lage deformations exhibit significant differences.

158 Using exact particular solutions and modal reduction in topology optimization of transient thermo-mechanical problems.

Max van der Kolk, Matthijs Langelaar, Fred van Keulen

In this work we focus on topology optimization of transient thermo-mechanical problems. These are, for instance, encountered during the design of high precision instrumentation. Due to the transient nature a backward time integration is required to obtain the adjoint sensitivities, which is undesired for large scale problems. Previous work has illustrated how the introduction of a reduced modal basis, with optional mode acceleration, allows to avoid the backward calculation to obtain the adjoint variables. To obtain accurate results and sensitivities, a relatively rich basis is required when using modal reduction, which can be reduced by introducing mode acceleration.

In order to reduce the computational effort even further, we have considered additional reduction approaches. In this work, an additional method is presented to be combined with the modal reduction and mode acceleration, while still eliminating the backward time integration. This approach focusses only on design cases where the heat loads can be expressed or approximated analytically by combinations of sinusoidal, polynomial, or exponential functions of time. The homogenous and particular solution of the state equation are solved separately. First, the particular solution is obtained using the full system, providing an exact solution to the quasi-steady-state response. Second, we introduce a modal basis to approximate the homogeneous solution, where only a relatively small set of thermal modes is required to obtain a proper approximation. Then, the exact particular solution is added to the approximated homogenous part to describe the system's full response. Neither forward nor backward time integration is required to obtain the response and its design sensitivities for the considered cases when the heat loads can be expressed by the considered analytical functions. The performance of the method is illustrated by several numerical examples.

159 A fast heuristic method using Hessian matrix for fluid topology optimization

Kazuo Yonekura, Yoshihiro Kanno

We study a heuristic optimization method using Hessian matrix for a density-based fluid topology optimization. Many researches in flow topology optimization are based on a gradient method which converges linearly. Convergence speed of a gradient-based method is slow near the optimal solution. In order to accelerate the convergence near the optimal solution, we utilize a Hessian matrix. We at first use a gradient-based algorithm to obtain a rough shape, and then we use a Hessian-based algorithm.

We formulate a fluid optimization problem using the lattice Boltzmann method and heuristically solve it. It is remarkable that the Hessian matrix of this formulation is a diagonal matrix. Therefore, the computation for the Hessian matrix and a search direction is fast. However, the Hessian matrix is not generally positive semidefinite since the optimization problem is a non-convex problem. Hence, we employ a gradient method for each component whose corresponding Hessian matrix element is not positive.

We solve some numerical examples and show computation time is drastically reduced. For example, it is reduced to about a half of that without Hessian matrix. In addition, the fluid and solid regions become clearly separated due to the Hessian-based algorithm.

160 Dynamic topology optimization based on finite strain visco-plasticity

Niklas Ivarsson, Mathias Wallin, Daniel Tortorelli

In this paper a dynamic finite strain visco-plastic model is implemented in a gradient based topology optimization algorithm. The kinematics relies on the multiplicative split of the deformation gradient, and the constitutive model is based on linear isotropic hardening visco-plasticity. To solve the dynamic mechanical balance laws the implicit Newmark-beta method is used together with a total Lagrangian finite element formulation. The optimization problem is regularized using a PDE filter and solved using the method of moving asymptotes (MMA). Sensitivities required to form the MMA approximation are derived using the adjoint method. To demonstrate the algorithm several designs are generated in which the absorbed visco-plastic energy is maximized subject to different load conditions. The numerical examples prove that inertial and viscous effects can successfully be combined with finite strain topology optimization.

161 Optimal positioning of a wall in an acoustic cavity using reduced models and surrogate based optimization

Luc Laurent, Antoine Legay

In the context of transportation design or civil ingineering, noise reduction is a constraint which is more and more included in the design processes. In order to easily take into account this constraint, new efficient technics have to be proposed for studying for instance the noise level in an aircraft cabin with respect with the arrangement within or for finding the optimal design for limiting the noise propagation. Thus, an approach based on the use of a finite element approach combined with surrogate based optimization is proposed.
The considered mechanical problem couples structural and fluid domain using an acoustic fluid governed by the Helmoltz's equation, a porous material modeled by the Biot-Allard's constitutive law and some thin walls governed by elasto-dynamic equation placed in the fluid. The air-structure problem is solved using Xfem in order to be able to consider an arbitrary structure placed in the acoustic cavity. After the building of the full coupled problem which takes into account the porous material, a reduced model is built using a Craig-Bampton's approach. This step leads to a significant reduction of the computational time.
Global optimization based on this mechanical problem requires a large number of calls to the mechanical solver. Therefore a surrogate-based optimization is used. The approach is based on the Efficient Global Optimization composed of two phases: (1) a kriging metamodel is built using only a few sample points and associated responses and (2) an iterative scheme using the expected improvement allows us to find the global minimum by adding smartly new sample points to the initial surrogate model.
The whole strategy has been applied on some 3D cavity on which the position of a wall is determined in order to minimize the mean quadratic pressure in a control volume. Some examples will be presented for illustrating the performance of the proposed approach.

162 Topology optimization of active transport fluid problems

Casper Schousboe Andreasen

This paper presents a methodology to use topology optimization for the design of microfluidic components for shaping the fluid flow to obtain certain target concentration profiles. By the use of a min-max formulation a robust performance across a wide range of Reynolds numbers facilitates applicability of the procedure to design application ready devices e.g. 3D printable. The transported matter may be passively transported with the fluid which is well documented in the literature[1]. In this work the transported matter engage actively with the flow introducing spatially varying properties which is novel in topology optimization. This could be e.g. a mixture of different fluids or transport of particles/bubbles in the fluid[2]. A monolithic formulation based on the Brinkman model capable of representing fluids with varying properties is discussed. The necessary interpolation functions to represent the physics reasonably well along with the modeling of the transported matter near the interfaces of the solid material is investigated. The representation of the physics is compared towards fluid-only models (commercial software) in terms of specific cases and the differences are discussed. Optimized designs of advanced flow components are presented and the performance of the these are validated by means of post-evaluations of the design using a body-fitted model.

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[2] Prosperetti, A., Tryggvason, G., Computational Methods for Multiphase Flow, Cambridge University Press, 2006

163 A fictitious physical model-based geometrical constraint in topology optimization for molding and milling

Yuki Sato, Takayuki Yamada, Kazuhiro Izui, Shinji Nishiwaki

Topology optimization has been applied to various design problems, including multiphysics problems and metamaterial design problems. However, when topology optimization results are applied to practical designs in industries, design engineers often must interpret and modify the optimized structures to satisfy manufacturability conditions. For example, in casting and injection molding processes, molded parts must have geometrical features that allow molds to be removed, and milling techniques can only be applied to workpiece areas that cutting tools can reach. These requirements can be expressed in geometrical conditions such as the need to avoid interior voids and undercut geometries in certain directions. Topology optimization should therefore incorporate this type of geometrical constraint in the optimization procedure and the scheme we propose here imposes a geometrical constraint so that a configuration that can be manufactured by molding or milling is obtained. In the proposed method, the geometrical constraint is implicitly described using a fictitious physical model. Consequently, although the optimized configuration will satisfy the constraint, the proposed method allows the constraint to be violated during the optimization procedure, which enables low dependency on the initial configuration. The fictitious physical model is described using an advection-diffusion equation, where material domains have virtual heat sources and the advection direction is aligned with a prescribed direction. Void regions with high fictitious temperatures then represent either undercut geometries or interior voids, so the fictitious physical model successfully imposes the desired geometrical constraint. Several numerical examples are provided to demonstrate the validity and effectiveness of the proposed method.

164 Integration of node-based shape optimization in computer-aided design workflows

Daniel Baumgärtner, Armin Geiser, Kai-Uwe Bletzinger

The current state of the art in shape optimization is dominated by approaches utilizing computer-aided design (CAD) or morphing boxes. On the contrary, node-based approaches have not reached the same industrial acceptance, although e.g. the Vertex Morphing Method showed with many practical problems promising characteristics like high optimization potential, minimum modeling effort or fast design space exploration. One major reason for this limited popularity is the missing link to CAD being the primary design tool in many industrial branches. This work discusses a way to close this gap.

More precisely, we present an automatic approach to transform results of a node-based shape optimization back to CAD so that a CAD-model of the optimized geometry is available. We thereby use the fact that in CAD workflows the geometry to be optimized is initially given

in CAD-format. Creating a CAD model of the optimized geometry hence may be regarded as a mapping operation instead of a pure design task. This is different as e.g. in topology optimization and allows a significantly better automation. Also, we make use of the fact that the geometry to be modeled by CAD is already known. It corresponds to the previous optimization result. So we may analyze the latter to e.g. estimate number and position of necessary control points. Note that this is still different to the case that CAD-based shape optimization was applied in the first place. Here the choice of the parameters severely influences the optimal solution possibly leading to an expensive re-parameterization or an unconvincing objective improvement.

General focus of this work is on the seamless integration of the Vertex Morphing Method in given computer-aided design workflows. Relevant demonstrators are chosen from aerospace (fluid optimization) and automotive industry (structural optimization). An outlook finally indicates the roadmap towards a framework unifying CAD-free and CAD-based shape optimization techniques.

165 Multi-Fidelity Optimization of Complex Physics Involved Engineering Systems

Christopher Fischer, Ramana Grandhi

This work presents an optimal design technique which allows for the use of multiple simulation models of varying physics and complexity (fidelity levels). An advancement of traditional Surrogate Based Optimization (SBO) techniques is intended to alleviate the computational cost associated with structural and multidisciplinary design optimization while maintaining a high degree of accuracy typically associated with fully coupled, nonlinear, complex physics-based models. This methodology, termed Bayesian Influenced Low-Fidelity Correction Approach to Multi-Fidelity Optimization, utilizes a combination of surrogate modeling, Bayesian statistics, and Trust Region Model Management (TRMM) techniques. A novel Bayesian Hybrid Bridge Function (BHBF) was developed to serve as the low-fidelity correction technique. This BHBF is a Bayesian weighted average of two standard bridge functions, additive and multiplicative. The correction technique is implemented in parallel with a modified Trust Region Model Management (TRMM) optimization scheme. It is shown that optimization on the corrected low-fidelity model converges to the same local optimum as optimization on the high-fidelity model in fewer high-fidelity function evaluations and ultimately lower computational cost. This work also extends the low-fidelity correction optimization beyond the traditional bi-fidelity (limited to 2 fidelity levels) optimization to that of a novel approach to handling optimization with multiple (2 or more) fidelity objective and constraint functions with commercial optimization solvers. It is shown that implementation of this Bayesian low-fidelity correction optimization approach results in high-fidelity results at a reduced computational cost. This is demonstrated on computationally different engineering design problems. First, a 27% computational savings over traditional optimization techniques is observed in the unconstrained minimization of thermally induced stresses in a quarter symmetric panel.

166 On structural shape optimization using an embedding domain discretization technique

Stefan Riehl, Paul Steinmann

The present contribution is concerned with the formulation and implementation of a method for structural shape optimization within an embedding domain setting. Thereby, the main consideration is to embed the evolving structural component into a uniform finite element mesh which is then used for the structural analyses throughout the course of the optimization. A boundary tracking procedure based on adaptive (or hierarchical) mesh refinement is used to identify interior and exterior elements, as well as such elements that are intersected by the physical domain boundary of the structural component. By this mechanism, we avoid the need to provide an updated finite element mesh that conforms to the boundary of the structural component for every single design iteration. Further, when considering domain variations of the structural component, its material points are not attached to finite element nodal points but rather move through the stationary finite element mesh of the embedding domain such that no mesh distortion is observed. Hence, one circumvents the incorporation of time-consuming mesh smoothing operations within the domain update procedure.
In order to account for the geometric mismatch between the boundary of the structural component and its non-conforming finite element representation within the embedding domain setting, a selective domain integration procedure is employed for all elements that are intersected by the physical domain boundary. This is to distinguish the respective element area fractions interior and exterior to the structural component. The method for shape optimization relies on an explicit geometry description for the structural component, and an adjoint formulation is used for the derivation of the design sensitivities in the continuous setting. We consider several numerical examples in which we assess the applicability of different selective domain integration procedures for the use in structural shape optimization.

168 Multidisciplinary Design Optimization of a Satellite Structure by Additive Manufacturing

Marius Bierdel

Launching a spacecraft into the desired orbit remains to be a critical and cost intensive effort. Therefore, Design Optimization in combination with Additive Manufacturing (AM) is a promising method to reduce the weight of Satellite Structures and consequently to increase the payload capacity of launch systems.
In this work we present a Multidisciplinary Design Optimization approach for a Satellite Structure carrying a variety of different payloads. Main design drivers are considered to be vibration loads during the launch period as well as thermal loads emerging from the temperature conditions in space. The structure was designed by combining both vibrational and thermal loads into the optimization model. To have preferably low design limitations in the numerical optimization process, where material is only placed at necessary areas, AM can offer a solution. The significant advantage using AM is the design freedom with almost no design restriction compared to conventional manufacturing methods. Selective Laser Melting as one of many AM-Methods was used to manufacture the optimized structure based on an aluminum alloy (AlSi10Mg).

As the validation process in the field of space engineering remains to be a significant part of the development process, the presented work will discuss the simulated results concerning the vibration response. More precisely, the calculated Eigen frequencies, the sinus response and random-response results are shown.

169 Finding optimized layouts for ribs on surfaces using the Graph and Heuristic based Topology Optimization

Dominik Schneider, Axel Schumacher

A promising approach in reducing weight is using thin shell structures with supporting ribs instead of thick shell structures, in order to only use the material where it is needed. Nevertheless, the optimization of these structures remains a big challenge, especially in crash load cases, because of material nonlinearities, contact and large displacements.
The Graph and Heuristic Based Topology Optimization (GHT) [1] presents a solution to generate better layouts for crashworthiness structures, but up to now it has mainly been used for the design of extrusion profiles with a uniform cross section. In order to apply this method to shell structures with ribs, the GHT is enhanced, so that the mathematical graph can represent ribs with information regarding their height, thickness, curvature and position. Through an adaptation in the process the ribs can be extruded to any surface that has no undercuts in the area of the new ribs.
During the optimization with the GHT competing layouts with new ribs are suggested by already existing heuristics, which change the topology based on expert knowledge regarding crash applications. In a final shape and sizing optimization the thickness, curvature and height of the ribs as well as the thickness of the surface that they are attached to can be optimized. The responses of the optimization can include any value that can be extracted from the simulation results (e.g. accelerations).
This feature enables finding better layouts for thin walled crashworthiness structures with supporting ribs e.g. manufactured by pressure die-casting or injection molding. Although causing a large simulation effort it is one of the few methods that can provide an optimized solution for structures in crash applications in consideration of a wide range of manufacturing constraints.

[1] Ortmann, C. and Schumacher, A. (2013) Graph and heuristic based topology optimization of crash loaded structures, Struct Multidisc Optim 47:839-854

170 MIXED-INTEGER LINEAR PROGRAMMING REFORMULATION APPROACH FOR GLOBAL DISCRETE SIZING OPTIMIZATION OF TRUSSED STEEL PORTAL FRAMES

Roxane Van Mellaert, Kristo Mela, Teemu Tiainen, Markku Heinisuo, Geert Lombaert, Mattias Schevenels

Structural design optimization can reduce both the consumption of natural resources by the construction industry and the engineering effort and therefore cost by automation of some of the most repetitive tasks in the design process. However, practicing structural engineers appear to be reluctant to adopt optimization as a daily design tool. One of the reasons is that real-world design problems are often governed by a number of practical constraints prescribed by the building codes. Some of these constraints are non-smooth, therefore most existing design optimization algorithms cannot take into account all these practical constraints. In addition, the optimization problem contains discrete design variables since the member profiles have to be chosen from a catalog of commercially available alternatives.

This paper presents a new method to find the global solution of combined truss-frame size optimization problems. The approach is based on a reformulation of the optimization problem as a Mixed-Integer Linear Programming problem (MILP) which is solved by means of a branch-and-bound method. A portal frame that consists of both beam and truss elements is adopted as a test case. The optimal sections of the portal frame have to be selected from a square hollow sections catalog. The design of the portal frame has to meet the requirements prescribed by the Eurocodes. These requirements are adopted as constraints by reformulating them as or approximating them by a linear equation. Not only the Eurocode constraints related to member strength and stability but also all Eurocode constraints related to the joints of the structure are taken into account during the optimization. As a consequence, a post-processing step to account for other constraints is avoided, therefore optimality is retained and additional engineering time is reduced. The optimization results are presented and the influence of the different Eurocode constraints on the optimal design is discussed.

171 On length scale control in topology optimization

Eddie Wadbro, Linus Hägg

Topology optimization aims at determining the layout of material(s) within a given design domain Ω so that a given performance measure is extremized. If there are two types of materials, for convenience referred to as material and void, to fill the design domain, then the objective is to find a region $M \subset \Omega$ such that we have material in M and void in the region $V = \Omega \setminus M$. The region M occupied by material is referred to as the design. In practical applications some regularity on M (and/or V) is typically required. One such regularity constraint is that M exhibits a minimum length scale. Over the years, many different methodologies aiming at imposing a minimum length scale on the design have been introduced. However, a precise definition of the minimum length scale has rarely been used, meaning that the length scale has mostly been qualitatively assessed. We propose a definition of the minimum length scale for subsets of a bounded convex design domain, and show that the length scale so defined is tightly linked to the operators of mathematical morphology.

We present numerical experiments for minimum compliance problems, where we use density based topology optimization with morphology mimicking non-linear filters (fW-mean filters) based on the harmonic mean to heuristically impose a minimum length scale on both phases (material and void). The optimized designs are essentially binary and exhibit a minimum length scale on both phases. Moreover, the numerical experiments suggest that in order for the imposed minimum length scales to be visible in the optimized designs, a not too aggressive continuation approach must be used.

172 Topology optimization of elastic wave barriers using a two-and-a-half dimensional finite element methodology

Cédric Van Hoorickx, Mattias Schevenels, Geert Lombaert

In order to reduce environmental ground vibration due to railway traffic, mitigation measures on the transmission path can be applied to impede propagation of ground vibration from source to receiver. Up to now, wall barriers with a rectangular cross section have mostly been studied. Presently used construction methods, however, allow for much more flexibility in the design geometry. Topology optimization is therefore used to discover novel design geometries.

Accounting for the three-dimensional character of the wave field is found to be essential when wave impeding barriers for railway induced vibrations are considered. The numerical solution of three-dimensional elastodynamic problems is, however, computationally demanding. To reduce the computational cost, the geometry of the problem is assumed to be uniform in the direction along the track. In this case, a computationally efficient two-and-a-half dimensional finite element (2.5D FE) approach can be applied, where the Fourier transform from the longitudinal coordinate to the wavenumber domain allows for the representation of the three-dimensional radiated wave field on a two-dimensional mesh.

In this contribution, topology optimization is applied to design wave barriers that minimize the three-dimensional wave transmission in an elastic medium. A homogeneous soil is considered, which is excited at the surface, and the design of a wave barrier on the transmission path is optimized to reduce the vibration levels in a nearby building. The optimization problem is solved using a gradient based approach and the adjoint method is used to enable an efficient calculation of the sensitivities. In this way, barrier designs are found which outperform rectangular wall barriers in the reduction of vibration levels. In the considered case study, the maximum RMS velocity in the building is reduced by 59% for the optimized barrier, while only a 19% reduction was found for a rectangular barrier.

173 Parametric Shape Optimization of Lattice Structures for Phononic Band Gaps

Fabian Wein, Michael Stingl

Topology optimization of phononic band gap structures (Sigmund & Jensen; 2003) yields periodic designs which suppress transmission of vibrations for a wide frequency range. However, the standard solutions are composed by solid material embedded within a weaker matrix material and are therefore bi-material designs.

It is inherently difficult to find connected solid/void band gap designs exhibiting a certain stiffness. Not only are the standard maximal band gap and maximal stiffness designs mutual exclusive, the band gap optimization is also known for non-smoothness issues caused by multiple and switching eigenvalues. Nevertheless, in (Bilal & Hussein; 2012) an in-plane design with a normalized band gap of 0.77 is presented as the best known design of its kind.

Here we propose a method, where a lattice is subject to parametric shape optimization and mapped onto a ersatz material model as used in topology optimization. From the parametric shape optimization, we have the assured connectivity of the structure and absolute control on the black and white contrast.

We obtain square symmetric designs with normalized band gaps up to 1.4, however porosity and stiffness significantly differs from Bilal & Hussein's design.

174 Development of a Multi-Objective Genetic Algorithm for the Design of Offshore Renewable Energy Systems

Ajit Pillai, Philipp Thies, Lars Johanning

This paper describes the development of a framework using a genetic algorithm in order to aid in the design of a mooring system for offshore renewable energy devices. This framework couples numerical models of the mooring system and structural response to cost models in order for the genetic algorithm to effectively operate considering multiple objectives. The use of this multi-objective optimization approach allows multiple design objectives such as minimum breaking load and the material cost to be minimized simultaneously using an automated mathematical approach. Through the application of this automated approach, a wider set of designs will be considered allowing the system designers to select a design which appropriately balances the trade-off between the competing objectives. In this work, a set of mooring designs that represent efficient solutions for the stipulated constraints are found and presented. The developed framework will be applicable to other offshore technology subsystems allowing multi-objective optimization and reliability to be considered from the design stage in order to improve the design efficiency and aid the industry in using more systematic design approaches.

176 Topology Optimization of Anisotropic Metamaterials to Realize the Desired EFC and Field Polarization

Byungseong Ahn, Hyung Jin Lee, Yoon Young Kim

Metamaterials are artificially designed to tailor various wave-specific phenomena that do not exist in nature by designing unit cells of microstructures smaller than wavelength. Especially, the non-resonance-based anisotropic elastic metamaterial has a great advantage in that it has a broad operating frequency region. Although the underlying wave physics can be revealed by the Equi-Frequency Contour (EFC), Field Polarization (FP) can be also critical for a certain class of wave tailoring such as mode conversion. However, no topology optimization based design of anisotropic metamaterial that simultaneously considers the EFC and FP has been reported earlier.

The aim of this study is to design anisotropic metamaterials by the topology optimization that simultaneously considers the EFC and FP. Field polarization refers to particle motion in an elastic medium, which determines the type of wave modes, longitudinal, shear or longitudinal-shear coupled modes. The target EFC and FP should be determined for specific design applications and some specific applications will be considered in this work. One of the main applications of the developed formulation is to design a unique mode conversion wedge that can transform an incident pure longitudinal wave mode to a pure shear wave mode when exiting the wedge. The validity of the developed formulation is confirmed and the role of FP is demonstrated by numerical examples.

177 Topology and Shape Optimization for a New Concept Vehicle Suspension Mechanism

Yoon Young Kim, Suh In Kim, Yong-Sub Yi, Joonhong Park

The vehicle suspension is designed to absorb the road impact for ride comfort and to guide vehicle tires for good driving performance. It may be classified as different types, such as the classical double wishbone type and the multi-link types. The aim of this study was to try to answer the following question: Can the topology optimization method produce new types of practically useful suspension mechanisms?
To synthesize 3-D vehicle suspension mechanisms by the topology optimization method, a number of kinematic requirements must be considered. For this study, most of actual kinematic design constraints, including those on anti-feature or bump-steering, were taken into account. Meanwhile, another constraint for the present suspension mechanism synthesis is to use a smaller design domain. Other kinematic constraints are basically the same as those used for suspension mechanisms designed on a regular design domain. In fact, the consideration of the layout size limitation was the key in obtaining a new concept suspension. Unlike most conventional suspension mechanisms, our new concept suspension designed by the topology optimization is shown to have an auxiliary link that does not directly connect a knuckle to the chassis frame. By using the screw theory, we could interpret that its existence makes the suspension restricted in a smaller space perform almost equally as the conventional linkage mechanisms in a standard-sized space. To the best of our knowledge, this study is not just the first successful industrial application of the topology optimization for mechanism synthesis but also suggests a new concept suspension mechanism. In this presentation, we will also discuss various numerical and theoretical aspects related to the topology optimization of suspension mechanisms, such as simultaneous topology and shape optimization.

178 Combined optimization of part topology, supports and printing orientation for additive manufacturing

Matthijs Langelaar

Additive manufacturing (AM) offers designers unprecedented form freedom and is rapidly being adopted throughout industry, in particular in combination with topology optimization (TO). However, conventional TO does not account for specific AM restrictions. Popular powderbed, layer-based AM processes require geometries to be self-supporting: all downward facing surfaces can only have a certain maximum inclination with respect to the printing direction. To meet this criterion, designers have 3 options: 1. Find a new orientation in which the geometry is self-supporting, 2. Modify the part design to render it self-supporting, 3. Add features (support structures) that result in a self-supporting geometry. Each method has downsides: reorientation affects printing time and cost, while design modification reduces performance of optimized parts. Supports add material and build time, and increase either weight or post-processing time. Finding a suitable compromise is presently a matter of experience and trial-and-error, which limits the full realization of AM benefits.

Thus, there is a need for TO approaches that take AM restrictions into account directly. With recently proposed TO for AM techniques, self-supporting part designs can be generated, but the chosen orientation strongly affects the results. Performing optimization for many orientations and choosing the best is possible, but comes with high computational cost.

In this contribution, we explore the idea of combining the optimization of part topology, printing orientation and support material placement into a single, integrated process. In this way, without resorting to an expensive exhaustive search, an optimal trade-off can be found between the loss of performance through part design adaptation and the added costs of supporting structures, for the best build orientation. We present the basic principle of our proposed formulation in a 2D setting, and illustrate its performance by several numerical examples.

179 Level Set Based Shape Optimization using Cut Finite Elements in Acoustics

Anders Bernland, Eddie Wadbro, Martin Berggren

A part of the outer boundary of an acoustic horn is updated iteratively to maximize its radiation efficiency, by minimizing the reflection coefficient in the interface to a waveguide. Traditionally, the finite element method uses a body fitted mesh to determine the properties of a given design. However, this requires a mesh update at each design iteration, which can be costly and is not always robust. In this project, a fictitious domain approach with an unfitted mesh is used, to eliminate the need for a mesh update.

The boundary of the horn is given by the zero-level contour of a level set function, and is allowed to cut through the elements. A crucial component in the method is stabilization, developed in the context of the CutFEM approach and needed to make the condition number of the system matrix bounded independent of the way the boundary cuts the mesh.

The derivatives of the reflection coefficient with respect to the level set are efficiently computed with an adjoint approach. Worth noting here is that the shape derivative is conforming to the finite element space when an un-fitted mesh is usednot the material derivative, as is the case using a fitted mesh.

The optimized design has significantly lower reflection in the whole frequency interval under consideration, but the shape is jagged and mesh-dependent. A smoother design is promoted by controlling the Laplacian of the level set function. The optimization results show some peculiar sub-wavelength structures, which have not been seen in previous analyses. With Tikhonov regularization, optimized designs without these features can be achieved at the cost of slightly higher reflection.

Although presently the project focuses on 2D acoustics, the procedure is also applicable to 3D acoustics and electromagnetics; in fact, the advantage of not re-meshing at every optimization step is more significant in 3D, since meshing takes a larger fraction of the computational time in three than in two dimensions.

181 A Cross-Entropy Optimization Algorithm for Continuous Function Based on Improved Sampling

Zhengyang Ma, Wen Yao, Yong Zhao, Yiyong Huang

In this paper, the Cross-Entropy (CE) optimization algorithm for continuous functions is studied. Aiming at the problem of computational efficiency caused by the large number of samples in Monte Carlo sampling, the Dynamic Weight strategy (DW) and the Adaptive sample Size strategy (AS) are proposed. The former can get the weighting coefficient of each sample by measuring the difference between the elite sample and the best sample, which can speed up the convergence rate of the algorithm. The latter can greatly reduce the number of calls to the objective functions by building relationship between the sample size and the standard deviation of elite samples, which can effectively improve the optimization efficiency. Finally, the validity of the proposed algorithm is verified by four unconstrained multimodal standard test cases and two constrained practical project examples. The results show that with similar capability to obtain the global optimal solution, the number of calls to the objective functions is reduced by 73.44%, 69.44%, 47.33%, 77.88%, 40.21% and 25.95% respectively compared with the traditional CE algorithm.

182 Multidisciplinary shape optimization of ductile iron castings by considering local microstructure and material behaviour

Jakob Olofsson, Riccardo Cenni, Matteo Cova, Giacomo Bertuzzi, Kent Salomonsson, Joel Johansson

During the casting process and solidification of ductile iron castings, a heterogeneous microstructure is formed throughout the casting. This distribution is highly controlled by process related factors, as chemical composition, local solidification conditions, and the geometry of the casting. Geometrical changes to the geometry of the casting thus alters the local mechanical behaviour, as well as the distribution of stresses and strains when the casting is subjected to load. In order to find an optimal geometry, e.g. with reduced weight and increased load-bearing capacity, this interdependency between geometry and local material behaviour needs to be considered and integrated into the optimization method.

In this contribution, recent developments in the multidisciplinary integration of casting process simulation, solidification and microstructure modelling, microstructure-based material characterization, Finite Element Analyses (FEA) with local material behaviour and structural optimization techniques are presented and discussed. The effect and relevance of considering the local material behaviour in shape optimization of ductile iron castings is discussed and evidenced by an industrial application. It is shown that by adopting a multidisciplinary optimization approach by integration of casting simulation and local material behaviour into shape optimization, the potential of the casting process to obtain components with high performance and reliability can be enabled and utilized.

184 Length-scale constraints for parameterized implicit function based topology optimization

Peter Dunning

A new method is proposed for imposing minimum length-scale (in both solid and void regions) in parametrized implicit function based topology optimization methods. Minimum length-scales are imposed using explicit constraints and the problem is solved using standard optimization techniques (e.g. mathematical programming). The effect of various parameters on the effectiveness of the proposed method is investigated using classic benchmark problems from the literature.

Length-scale control has been identified as an important feature of topology optimization algorithms to provide regularity to the problem and enable the inclusion of an important class of manufacturing constraints, namely maximum and/or minimum feature sizes. Various methods have been developed and successfully applied to density-based methods, such as those based on filtering schemes. Topology optimization methods using implicit functions have gained popularity over the last decade due to several advantages over density based methods, such as smooth boundaries and elimination of some numerical issues like checkerboard patterns. However, length-scale control is not inherently addressed when using implicit functions and several techniques have been proposed to resolve this. For conventional type level-set methods the implicit function is defined as a signed distance function. This property can then be exploited to create successful schemes that impose minimum and/or maximum length-scale in both solid and void regions. However, no general scheme currently exists to explicitly impose length-scale constraints for parameterized implicit function methods, where the signed distance property is not preserved during optimization. This short-coming will be addressed in this presentation by the introduction of a new method.

185 Robust optimization of adiabatic power splitters.

Cédric Durantin, Karim Hassan, Alain Glière

Silicon photonics is a very active research field owing to numerous applications in on-chip optical communications. Adiabatic power splitters carry out one of the basic optical functions, namely efficiently sharing optical power between two output waveguides. Compactness and robustness to fabrication uncertainties are the two main challenges addressed during the design, nowadays based on numerical simulation. They are constrained by the adiabaticity criterion, which is often ensured by a long coupling zone, that increases the overall size of the component.
The novelty of this work lies in the use of a metamodel-based worst-case scenario optimization method, which leads to the rapid design of compact and robust adiabatic splitters. The component behavior is modeled by means of 3D beam propagation method calculations. This numerical model is replaced by a metamodel, which is trained over a five geometrical parameters design space. The output to surrogate is the worst deviation to a 50/50 power splitting ratio over four wavelengths in the studied bandwidth. This value assesses the robustness of the component, which is highly desirable for large wafer-scale production. A multi-objective optimization procedure finds a set of solutions that minimizes the power splitting imbalance

(the prediction value of the metamodel) and the coupling length of the device (a design parameter). A k-means clustering algorithm then selects five points among the solutions, which are further evaluated and added to the training dataset of the metamodel. This sequence is iterated until the solutions of the multi-objective algorithm vary less than a given tolerance. An optimal device has been obtained at a reduced computational cost and afterwards fabricated and characterized. Its performances and robustness are discussed and compared to that of a conventional design.

187 Adaptive random field discretization for optimization under uncertainties.

Sylvain Dubreuil, Christian Gogu, Nathalie Bartoli, Thierry Lefebvre

Considering uncertainties in the design and optimization of complex systems is still challenging due to the various ways the uncertainties can affect the system. We consider here the problem of an objective function defined on both a continuous parametric space (the design space) and on a stochastic space (modelling the uncertainties). Hence, the objective function can be seen as a correlated random field over the design space. Furthermore we consider the case where the objective function is computationally expensive to evaluate and can only be obtained in a limited number of points in the design space, to be appropriately chosen. We propose an adaptive approach for choosing these points in order to accurately represent any realization of the random field in promising areas with respect to the global optimum. To derive this approach we investigate the random variables modelling the minimum value of the field and its position. These two random variables are uniquely defined and contain relevant information about the robustness of the system that can be useful in particular in view of a new definition of a robust optimum.
The proposed discretization approach aims at focusing the computational budget over the areas of the parametric space where the minimum is likely to be. To this purpose the random field modelling the quantity of interest is represented using Karhunen-Love and polynomial chaos expansions. Moreover, an original adaptive enrichment scheme based on Kriging is proposed. Advantages of this new approach with respect to accuracy and computational cost, compared to classical random field discretization schemes are demonstrated on several numerical examples. An application of the proposed approach to the aerodynamic optimal design of an aircraft wing is also provided.

188 Bayesian Estimation of Steel Material Properties under Cyclic Loading Condition

Ehsan Adeli, Bojana Rosic, Hermann G. Matthies

The evaluation of the performance of engineering structures includes models of behavior of materials, structural elements, loadings, external excitations etc. In assessment studies, there are several classes of uncertainty related to the lack of information on loading conditions/excitations, behavior of material properties over time, geometry and boundary conditions which may be identified and reduced by the means of quality control or system monitoring and identification. [1] In this work the focus is on the propagation of the a priori parametric uncertainty into a viscoplastic model describing the behavior of steel structure and its quantification in the model response. To do so, the non-intrusive Stochastic Finite Element Method (SFEM) based on polynomial chaos is applied for different test e.g. the relaxation and creep tests. [2] Once the stochastic model, which is a more realistic model than the deterministic model, is provided, the probabilistic description of the model parameters can be narrowed using measurement data such as displacement/strain via Bayesian approach. In this study, a polynomial chaos based Bayesian method is employed. [3] The results are compared with Markov Chain Monte Carlo method.

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189 Buckling length in mixed-integer linear frame optimization

Teemu Tiainen, Kristo Mela, Markku Heinisuo

In structural optimization of trusses and frames, the member profiles have to be selected from material supplier's selection. This means that the optimization problem becomes discrete. The discrete frame optimization problem can be formulated as mixed-integer linear program (MILP) and thus solved for global optimality using well-known deterministic methods such as branch-and-cut. Within the formulation it is possible to include member buckling constraints. When using design standards as basis for member buckling resistance evaluation, the critical forces or buckling lengths of the members are required. Buckling length can be determined using many methods, both numerical and analytical. Regardless of the method, buckling length of a single member is dependent on surrounding members' stiffness which makes it practically impossible to include the correct buckling lengths in MILP formulation directly. In general, the question of buckling length in frame optimization has rarely been discussed in the literature. Therefore, in this paper, an iterative approach to determine the correct buckling lengths is presented. In this approach, the MILP optimization is run several times. Linear stability analysis is performed between MILP runs to update buckling length data. The performance of the proposed method is illustrated in example calculations. The example structures are steel frames and Eurocode 3 is used as basis for member resistance constraints. In the examples, the method converges with a relatively low number of iterations.

190 Optimal designs with optimal materials

Seth Watts, Daniel Tortorelli

The canonical topology optimization problem specifies the solid material(s) a priori and then seeks to arrange it (them) along with void space within a domain in order to extremize the objective function while respecting any constraints. Upon convergence, one can say that the design is (at least locally) optimal, given the choice of material(s). However, since real materials often have inherent trade-offs, such as stiff materials often being dense and/or brittle, the

selection of material(s) for a given design problem may be non-trivial when multiple material properties are important. Two common examples include stress-constrained compliance design, in which both stiffness and yield strength are important, and inverse homogenization design of meta-materials, which might consider (say) both elasticity and electromagnetism. Thus, there is the potential for improved designs if the optimizer can select the material(s) to be used, as well as arranging it (them) within the design domain. Ideally, the optimizer may choose any material(s) from all those available for manufacture.

We use the binary-coded parameterization to efficiently encode many materials for the optimizer to consider, and impose (among other constraints) a limit on the number the optimizer may choose to use in a given design. By varying this limit, the designer can explore the improvement in the objective function as the number of materials is increased; if it plateaus, an optimal design with optimal materials has been achieved. If material prices and the marginal cost to use another material are known, then the design can be optimized for cost at a given performance, or retooling costs may be justified by increased performance.

We present our formulation and demonstrate its use in common 2D design optimization problems. Our implementation uses a density parameterization, but the formulation may also be used in level set, geometry projection, or other parameterizations.

191 Topology Optimization with integrated casting simulation and parallel manufacturing process improvement

Thilo Franke, Sierk Fiebig, Karsten Paul, Thomas Vietor, Jürgen Sellschopp

Affordable lightweight design is one of the key topics for the automotive future. Increasing worldwide competition, stricter legal guidelines and weight-intensive electronic components of new drive systems require lighter and more economic chassis components. Aluminum parts enable activation of lightweight design potentials in terms of good material properties and affordable costs. To ensure cost-effective production of cast parts, a lean and efficient manufacturing process is necessary. Furthermore, a lighter design lowers the material costs of the part directly. Topology optimization offers a lightweight design in a fast automatic procedure and is nowadays used at the beginning of many development processes for cast parts. Commercial optimization software considers the castability of the part only insufficiently on the basis of simple geometric rules. Thus, manual modifications for the manufacturing process are needed.

In this work, an integration of a casting simulation into the topology optimization is presented. This leads to a considerably increased castability of the part. In parallel to the stress-based optimization in order to improve the mechanical properties, turbulence and vorticity during the filling process are reduced, cold run is prevented and a directional solidification is ensured. This procedure does not only result in a castable lightweight design but it also provides a basis for an economic casting process. For that reason, the casting process is adapted in parallel to the parts optimization. The geometry is reduced to a two-dimensional graph and an innovative functional is deduced from it. Its maximization will identify the ideal pouring position as well as the positions and sizes of necessary feeders. This method is discussed with the help of a corner modules optimization. The resulting design is characterized by a low weight, a geometry suitable for economic casting and an easy transformation into a CAD-part in a short development process.

192 Layout Optimization for Stiffened Plates on a Simple Stiffener's Modellation

Dong Wang, Zhenghao Li

In order to enhance the mechanical properties of metallic thin-walled structures, stiffening ribs or stiffeners are widely employed in practice to improve the behaviors of a bending plate. Previously, structural topology optimizations were often applied for stiffeners introduction and developing trend on various objectives, such as minimization of the deformations, stresses, or maximization of the buckling loads or natural frequencies with the design constraint of the structural weight or cost.

In this work the stiffeners are assumed to be embedded initially in the plate, but arranged arbitrarily. A two-stage optimization methodology is proposed for the optimal layout (position and size) design of stiffeners based on the design sensitivities analysis. The objective is for maximization of the structural natural frequency subject to the deformation constraint when the stiffened plate is loaded statically. First, for the purpose of a simple solution of the optimization problem, the stiffener in a bending plate is modeled approximately as a series of flexible point supports such that the transverse movement of the straight stiffeners can be carried out effectively upon the design sensitivity analysis developed earlier. Then, by the stiffeners shifts within the plate, the natural frequency of the stiffened plate can be improved significantly while its weight is retained essentially in the process of the stiffeners movement. The equivalent stiffnesses of the supports can be achieved in accordance with the restrained boundaries of the stiffeners.

Next, the stiffener height is scaled to meet the constraint imposed on the deformation caused by the external loads. It turns out from the numerical examples that the optimal layout design of the stiffeners is very efficient with a great enhancement of the mechanical properties of the stiffened plate in respect to its weight.

193 Truss-like structures optimization under buckling constraints using frame elements with anisotropic cross sections

Florian Mitjana, Sonia Cafieri, Florian Bugarin, Christian Gogu, Fabien Castanie

Structural optimization is of increasing interest in a wide variety of application fields. In this paper, we focus on truss-like structural optimization under stress and buckling constraints. We use frame elements and investigate the impact of considering anisotropic cross sections, which allow better tailoring of the cross section to the loading applied and have thus the potential to lead to additional weight savings. We propose a formulation of the mixed-integer nonlinear optimization problem with a tailored objective function and decision variables involving cross sectional dimensions, considering more degrees of freedom than what is generally done. Moreover, a new algorithm tailored to this considered problem is proposed. Numerical results show that the proposed approach provides interesting structural weight savings.

194 Simultaneous Analysis and Design formulation for sizing optimization problems under many dynamic loads

Susana Rojas Labanda, Mathias Stolpe

A Simultaneous Analysis and Design (SAND) formulation for transient dynamic response in structural optimization is described and compared to the classical nested approach in terms of computational time and efficiency. The objective function is the mass/cost of the structure while constraints on displacements and stresses at each time step and fundamental frequencies are included. In this formulation, both the state and the design variables are considered as independent variables in the optimization problem. The state variables include the displacements, velocities and accelerations at each time-step in the simulations. In order to relate them, several techniques can be used. In particular, the finite difference methods and the Newmark method are considered. Similar to the SAND approach for static loads, this relationship together with the transient equations are included as explicit equality constraints. Thus, the transient equations will be satisfied at the end of the optimization process when all constraints are satisfied. One of the biggest advantages of this formulation is that both Jacobian and Hessian matrices are sparse and computationally much cheaper than in the nested approach. On the other hand, the optimization solver needs to handle problems with a large number of variables and constraints. In order to improve the efficiency of the solver, the mathematical structure of both Jacobian and Hessian must be exploited. Due to the characteristics of the optimization problem, efficient second-order methods such as interior points are ideal to solve this problem.

The formulation of the problem is tested for sizing optimization of wind turbine jacket support structures. In this type of problems, the transient equations must be solved for long simulation times and short time steps in order to obtain accurate results. Since the computational time of this formulation increases with the number of time steps, model reduction techniques are considered.

195 Comparison of fatigue constraints in optimal design of jacket structures for offshore wind turbines

Jacob Oest, Kasper Sandal, Sebastian Schafhirt, Lars Einar S. Stieng, Michael Muskulus

The objective of this paper is to compare analysis models and fatigue constraint formulations in optimal design of jacket structures for offshore wind turbines. Static analysis with an approximated fatigue constraint is compared with fatigue constraints based on quasi-static and dynamic analysis.

A structural design problem is formulated to minimize the jacket mass subject to fatigue constraints. The structure is modelled by Timoshenko beam finite elements, and the cross sections of the members are considered as design variables. The loads on the wind turbine are pre-computed and applied to the wind turbine tower top as time series. The static problem translates the load time series into static damage equivalent loads, and uses a fatigue equivalent stress constraint to obtain approximate fatigue constraints. The quasi-static and dynamic problems compute fatigue using rainflow counting on the stress histories. The optimal design problems are solved in the nested formulation using the open source solver IPOPT. Optimized designs are subsequently checked by a full aero-elastic simulation to validate the design or generate new loads for a second optimization run.

The quasi-static and dynamic approaches perform similar both in terms of computational cost and optimized designs, with the quasi-static approach being slightly faster. The static approach is more than three orders of magnitude faster than the quasi-static and dynamic approaches. However, the computational superiority of the static approach is paid for by a lack in accuracy in optimized mass.

The static approach is suitable in a conceptual design phase where many design concepts need to be compared in an approximate manner. When a conceptual design is chosen, the quasi-static and dynamic optimization methods are both suitable to optimize the design further.

196 Structural optimization based on stress constrained topology optimization

Vasily Chedrik, Sergei Tuktarov

The most general structural optimization method is topology optimization that is used to find in a design domain an optimum material distribution. The geometry and shape of the final design is the result of topology optimization. The earlier authors papers show that the significant weight reduction is achieved after sizing optimization with stress/buckling/aeroelasticity constraints of the structural layout after interpretation of the topology optimization result. The sizing optimization must be done because topology optimization was focused primarily on global structural behavior such as structural compliance for the most critical load case. So topology optimized design did not satisfy local failure criteria under the applied load conditions.

The purpose of this research is to develop novel approach to structural optimization in which stresses must be considered in topology optimization stage. It is known that stress-based topology optimization problems are difficult to solve because a large number of constraints must be considered and stress is highly nonlinear with respect to design variables. In this research, global functions are used to approximate local stresses in zones of stress concentration. These zones are found after first stage of topology optimization which is based on free-size fully-stress design algorithm that leads to large values of densities in the zones. The second stage of topology optimization is to determine material distributions in zones of stress concentration with taking into account gauge constraints on maximum of densities.

The proposed method is demonstrated on the set of known examples such as L-bracket, cantilever and MBB structures. An example of design of aircraft wing illustrates full approach to structural optimization which includes new stress-based topology optimization, engineering interpretation and sizing optimization. It is shown that the developed approach is highly efficient and it may give better optimal solution.

197 Coupling of Computer-aided Methods: Supporting Product Developer during Embodiment Synthesis

Albert Albers, Markus Spadinger, Manuel Serf, Stefan Reichert, Steffen Heldmaier, Micha Schulz

The high complexity during the development of new product generations is nowadays one of the biggest challenges in the product creation process. One solution to support the product developer is to use computer-aided methods. These methods allow to simulate various physical behaviors in order to predict the validity of the new product generation. Furthermore, the integration of those methods into optimization procedures allows to generate optimal design proposals. One example for this is the topology optimization. But, however, those methods are limited, because they do not consider the results of previous simulations or information from other domains in a fully-automated way.

This work proposes a strategic approach to overcome the challenges of today by coupling different simulation and optimization methods. By this, new coupled computer-aided methods are developed to support the product developer during embodiment synthesis. The presented coupled methods show the benefits of this strategy.

For example, the linkage of the topology optimization with the form fill simulation was carried out. Hereby, the calculation of the fiber orientations is done in each iteration of the topology optimization process. This results in initial design proposals for parts made of fiber-reinforced polymers, which consider the local anisotropies caused by the manufacturing process. Another example for the successful coupling of existing methods is the merging of topology optimization and multi-body simulation. This allows to reduce the energy consumption of accelerated systems by minimizing the inertia of the moving structures within the topology optimization process.

The presented coupled computer-aided methods are based on established and commercially available tools. This ensures a short-term availability of the developed methods for product developer. Therefore, additional qualification measures and long training periods are not required.

198 Bi-level approach to structural optimization of aircraft wing with stress and flutter constraints

Kirill Balunov, Vasily Chedrik

Structural design of aircraft wing is a very complex problem. This is due to that many operating constraints arising from different technical disciplines determine the performance of an aircraft. Multidisciplinary design optimization is used to take into account cross-disciplinary interactions to obtain optimal solution for such problems. This process is very time-consuming and, often in practice, it is necessary to simplify the design problem by using mathematical models of different fidelity for different design problems and levels.

The objective of the paper is to present an approach to structural optimization problems based on bi-level structural modeling. In this bi-level approach loads analysis and structural optimization with flutter constraints are performed by using low fidelity structural models. The structural optimization with stress and displacement constraints are accomplished on high fidelity finite element model. The questions of agreement of the computational models of different fidelity, such as beam model, equivalent plate model, shell/beam and finite element model are considered. A comparative analysis of advantages and disadvantages of such mathematical models to increase an accuracy of modeling of the structural flexibility was performed.

Numerical examples are presented for design of high aspect ratio wing with aeroelasticity and strength requirements. Sizing parameters of structural elements and parameters which define planform are obtained. The structural weight of the optimal wing is about 7.1% less than one for optimized baseline configuration (without optimization of wing shape). The application of the developed bi-level approach with using beam and shell finite element models of aircraft wing allows significantly reduce computational time in comparison with using one high fidelity model in structural optimization with stress and flutter constraints.

199 Layout Optimization of Frames in the Presence of Self-Weight: A New Formulation

Helen Fairclough, Matthew Gilbert, Andy Tyas, Aleksey Pichugin

Classical numerical layout optimization techniques can be used to find a highly accurate approximation of the minimum volume structure required to equilibrate a prescribed system of loads and supports. However accurately representing the self-weight of physically large structures (e.g. long span bridges) has to date been problematic.

In the field of truss layout optimization previous workers have assumed that the self-weight of each member is applied at its end points, with the member implicitly assumed to be capable of resisting bending along its length. This can lead to anomalous results, with the true volume of material required for a given problem being under-estimated.

In this article, self-weight is assumed to be applied continuously along the length of each member. This requires the use of members which take the forms of equal stress catenaries. The equal stress catenary form is defined by the strength-to-weight-ratio of the material, and the span of the element, and is linearly related to the force being transmitted. Therefore the resulting formulation is a linear programming problem, allowing the use of efficient optimization algorithms capable of solving very large-scale problems. The largest problems considered here have over 2 billion potential members.

The new formulation is applied to various structural engineering design problems involving long spans. It is shown that the method can identify new forms which are much more efficient than traditional forms, and that the amount of material saved increases at longer spans. Additionally, it is shown that it is possible to identify the longest span possible for a given material and prescribed system of loads and supports.

201 Sizing optimization of an offshore wind turbine jacket under dynamic loads considering stress and eigenfrequency constraints

Alexander Verbart, Kasper Sandal, Mathias Stolpe

Minimizing the cost of wind energy is the main objective of wind energy research. It is expected that substantial costs saving can be obtained by optimizing offshore wind turbine support structures such as jackets. The main challenge is that these structures have to meet several structural criteria, such as strength, fatigue and eigenfrequency. Since wind turbines are subjected to many dynamic loading conditions this leads to an intractable amount of constraints. For example, stress constraints need to be satisfied at every time instant. The objective of this work is to develop numerical methods that can succesfully optimize support structures subjected to dynamic loads.

We apply sizing optimization to a jacket modeled by 3D Timoshenko tubular beam elements. The structure is subjected to dynamic wind loads, which are obtained from aero-elastic simulations. The optimization problem is to minimize the mass subject to time-dependent stress constraints and eigenfrequency constraints. Design variables are the diameter and thickness of each tubular member. The number of nonlinear constraints $\mathcal{O}(1e6)$ greatly exceeds the number of design variables $\mathcal{O}(1e1)$.

In this work, we tackle the large number of constraints by solving a sequence of reduced optimization problems to optimality using gradient-based optimization. Every reduced optimization problem considers a working set, which is a small subset of critical constraints out of the complete set of constraints. After solving every reduced problem to optimality, a full analysis is performed on the optimized design and the all constraint function values are calculated. Critical constraints are added to the working set and a new sub-problem is solved until there is no constraint violation. We demonstrate the approach by optimizing an offshore wind turbine jacket and comparing the result with a reference design.

202 Sensitivity-based design optimization of electric motors

Peter Gangl

We consider the design optimization of an electric motor by means of topological and shape sensitivity analysis and present an efficient optimization tool consisting of two stages: In a first step, the optimal topology is determined by a level set approach which is based on the topological derivative, whereas, in the second stage, shape optimization together with an interface finite element method is used as a post-processing in order to get smoother optimal designs.

Given a shape functional which depends on the shape of a domain, the topological derivative at a fixed interior point of this domain describes its sensitivity with respect to an introduction of a small hole around this point. We present the topological derivative for a PDE-constrained optimization problem which is subject to the problem of nonlinear magnetostatics and discuss its relation to the sensitivity of a functional with respect to a perturbation of the material coefficient.

In contrast to the topological derivative, the shape derivative measures the sensitivity of a shape function when the boundary of a domain is moved into the direction of a given smooth vector field. We present the shape derivative for the same nonlinear problem. In the course of the shape optimization procedure, the material interface between the ferromagnetic and the air region of the motor is successively updated. In order to accurately solve the state and adjoint equation of the optimization problem in each iteration of the algorithm by the finite element method, the material interface should be captured by the finite element discretization. We present a local mesh modification strategy which yields optimal order of convergence as the mesh size tends to zero.

203 Design of Bone Plates for Mandibular Reconstruction Using Topology and Shape Optimization

Michael Seebach, Felix Theurer, Peter Foehr, Constantin von Deimling, Rainer Burgkart, Michael Friedrich Zaeh

Tumors in the maxillofacial area and cancer therapy in general can lead to necrosis of the lower jaw (mandible). To prevent tumor spread and infection the necrotic bone and surrounding soft tissue needs to be surgically removed. To restore normal function and appearance of the jaw, the resected mandible is reconstructed using autologous (originating within the body) bone graft from the fibula and titanium bone plates for the osteosynthesis (fixation) of the bone fragments.

Currently, standard bone plates are used that have a high volume or, in the case of mini plates, show a high risk of implant failure. The introduction of optimized, patient-specific bone plates helps to decrease intraoperative stress for the patient and facilitates an improved patient recovery by providing sufficient stabilization of the bone fragments as well as high stiffness and durability of the implants while minimizing the volume of the implanted material. Within this publication, the design process of the topology optimized bone plates is shown. First, a finite element model of the reconstructed mandible was created using standardized, synthetic bone models, boundary conditions based on a custom made, biomechanical testing rig for the mandible and different biomechanical load cases. Then, the volumes of the initial design areas of the bone plates were reduced using topology optimization and the design of the final bone plates was developed including shape optimization.

Finally, a design validation of the optimized bone plate designs was conducted by a non-linear finite element analysis. A reduction of total volume of 44.9 % was achieved by a maximum stress in the bone plates for the different load cases of 230.00 MPa to 797.10 MPa concluding high fatigue strength of the implants. The uneven load distribution over the screws of each bone plate could be reduced by up to 73.72 % preventing overloading of one screw and thus reducing the risk of screw failure.

204 Big-Data based rule-finding for analysis of crash simulations

Constantin Diez, Philipp Kunze, Dirk Toewe, Lothar Harzheim, Axel Schumacher

Efficiently and systematically extracting knowledge from design of experiments studies in the field of vehicle crash simulation is increasingly challenging due to the number and size of the simulation models and the complexity of the occurring mechanisms. As an alternative to common statistical postprocessing, this paper proposes the usage of data-mining methods from the field of knowledge discovery in databases to condensate important effects and give insight into their origins.

Before application of mining techniques, one has to separate the data into two groups regarding a criterion. This criterion may be in general a boolean condition for the response of interest, such as a response with specified bounds, or the affiliation to specific classes, such as different deformation behaviors. For the latter case, the categorization by deformation behavior is exemplarily demonstrated by clustering of simulation results with similar distributions of plastic strain.

Once the simulation runs have been separated into two groups, our proprietary rule mining technique can extract rules. A rule is a classical IF-THEN condition, where the THEN-part is the specified criterion and the IF-part are humanly readable boolean conditions of variables (e.g. "if variables $x < 50$ AND variable $x > 20$") fulfilling the criterion (e.g. then reponse < 15). All discovered rules need to be filtered regarding certain rule mining criteria, so that an engineer is only confronted with a few reasonable, interesting and important rules. The filtered rules usually contain only few variables, which is also a benefit from decision tree learning in the background.

In contrast to optimization the result of this technique is not a design point but multiple design subspaces. An engineer may now either choose a design point within these spaces directly or use the variable ranges as constraints for an additional optimization.

206 SIMP based Topology Optimization for Injection Molding of SFRPs

Felix Ospald, Roland Herzog

Today there exists a huge demand for technologies which enable and facilitate the mass production of fiber reinforced composites. Injection molding of Short Fiber Reinforced Plastics (SFRP) is a quite popular method especially in the automotive industry, providing high stiffness levels on the one hand and complex moldable shapes on the other hand. Due to the high cost of mold production and injection molding machines, nowadays lots of research is done to improve models and to develop software for the simulation of this process. This allows to detect problems with the mold design and optimization of the part performance and quality at an early stage of the development.

In the case of SFRP injection molding, the mechanical properties of the finished part are mainly influenced by the local fiber orientation, which itself depends on the shape/topology of the part. We investigate an approximate approach for compliance-based topology optimization for such parts, where we replace the costly filling and fiber orientation simulation by the solution of an eikonal equation which determines the principal fiber orientation approximately. Sensitivities for compliance minimization are derived for the classical Solid Isotropic Material with Penalization (SIMP) method in combination with a transversely isotropic material law. The optimization problem is then discretized using the Finite Element Method and solved using a projected gradient method.

207 Topology optimization of structures by the level set method taking into account thermal residual stresses induced by additive manufacturing.

Lukas Jakabcin, Grégoire Allaire

Among additive manufacturing processes we consider selective laser melting process (SLM) since it can create very sophisticated shapes by adding successive powder layers which are melted by a heat source, like a laser or an electron beam. During this additive process, large temperature gradients are generated in the built structure which consequently, by thermal expension, induce internal stresses which are highly undesirable.

In this work we investigate the shape and topology optimization of a final structure combined to the minimization of thermal residual stresses in the intermediate shapes generated by the additive process. The performance of the final shape is, as usual, evaluated by standard linearized elasticity and a classical objective function (say, compliance). However, the intermediate shapes are simulated by a transient thermo-elasto-plastic model coupled to the heat equation. The thermal residual stresses for the final structure are the plastic stresses at the end of the building process.

The intermediate shapes are mixture of the thermo-elastic powder and of the created thermo-elasto-plastic material. The final form is only elastic with residual stresses but without any further thermal effects. The laser or electron beam, the heating and cooling effects are modeled via a simple linear heat equation.

The shape derivative is computed by an adjoint method and the adjoint problem involves a backward heat equation coupled with an adjoint thermomechanical equation. The optimal shape is tracked by a level set algorithm. We illustrate our results by several numerical simulations.

208 Application of Digital Image Correlation to Material Parameter Identification

Nielen Stander, Katharina Witowski, Andre Haufe, Martin Helbig, David Koch, Christian Ilg

Digital Imaging Correlation (DIC) is an optical method which provides full-field displacement measurements for mechanical tests of materials and structures. It can be used to obtain temporal displacement, deformation or strain fields from an experimental coupon and can be combined with Finite Element Analysis to identify the constitutive properties of a material [1].

Because DIC-based parameter identification is an inverse process, optimization is used to obtain the parameters which will minimize the discrepancy between the measured and the computed fields. The Mean Squared Error functional typically used [1] is: $f(x) = \sum_{j=1}^{n} \|\varphi_j(x) - \tilde{\varphi}_j\|^2$ where $\varphi_j(x)$ is a vector of nodal displacements/strains (for computation and experiment) at a number of observation points and n is the number of observation states. The functional can be augmented to incorporate global force-displacement measurements or any other functional resulting in parameter identification based on DIC.

As part of this research, the DIC methodology was implemented in the LS-OPT©code utilizing the following main features: (i) multi-point responses and histories, (ii) the alignment and automatic mapping of points to an FE model. An interface is provided for importing ARAMIS/GOM® (a popular commercial optical test package) test results.

As a first test example, a parameter identification problem was constructed using a flat tensile bar with a hole in which the deformation field history was used as "test" input to recover the original parameters. Further parameter identification examples will be presented at the conference.

[1] Mahnken, R., Stein, E. Parameter Identification for Finite Deformation Elasto-Plasticity in Principal Directions, Comput. Methods Appl. Mech. Engrg, 147, 17-39 (1997).

209 How to deal with mixed-variable optimization problems: an overview of algorithms and formulations

Julien Pelamatti, Loïc Brevault, Mathieu Balesdent, El-Ghazali Talbi, Yannick Guerin

Real world engineering optimization problems often involve discrete variables (e.g., categorical variables) characterizing choices such as the type of material to be used or the presence of certain system components. From an analytical perspective, these particular variables determine the definition of the objective and constraint functions, as well as the number and type of parameters that characterize the problem. Furthermore, due to the inherent discrete and potentially non-numerical nature of these variables, the concept of metrics is usually not definable within their domain, thus resulting in an unordered set of possible choices. Most modern optimization algorithms were developed with the purpose of solving design problems essentially characterized by integer and continuous variables and by consequence the introduction of these discrete variables raises a number of new challenges. For instance, in case an order can not be defined within the variables domain, it is unfeasible to use optimization algorithms relying on measures of distances, such as Particle Swarm Optimization. Furthermore, their presence results in non-differentiable objective and constraint functions, thus limiting the use of gradient-based optimization techniques. Finally, as previously mentioned, the search space of the problem and the definition of the objective and constraint functions vary dynamically during the optimization process as a function of the discrete variables values.

This paper presents a comprehensive survey of the scientific work on the optimization of mixed-variable problems characterized by continuous and discrete variables. The strengths and limitations of the presented methodologies are analyzed and their adequacy for mixed-variable problems with regards to the particular needs of complex system design is discussed, allowing to identify several ways of improvements to be further investigated.

210 Topology optimization of a cervical fusion cage with graded porous Titanium

Ahmed Moussa, Damiano Pasini

Anterior cervical discectomy with fusion is a common surgical treatment that can relieve patients suffering from cervical spondylosis. Although autologous bone graft is considered to be the gold standard in achieving fusion, the associated morbidities in the short and long periods have motivated the search for alternative implants and materials, such as carbon-fiber, titanium alloy (Ti), ceramic and polyetheretherketone (PEEK). One serious complication with these materials is subsidence, the perforation of the cervical vertebra inflicted by the implant. To address this problem, this work introduces a fusion cage made of a graded porous titanium that minimizes the risk of subsidence associated with the fully solid implants. The implant microarchitecture is obtained through a scheme combining multiscale mechanics and multi-constraint density-based topology optimization. Asymptotic homogenization is used to capture the multi-scale mechanics of the implant, with the tetrahedron cell used as building block of the material microarchitecture. The results show that subsidence on the anterior region of the inferior surface for the graded lattice implant is 5% lower than that of a conventional fully dense titanium cage implant. In addition, the von Mises stress on the anterior region of the former is 10% higher than that of the latter, thereby potentially alleviating the stress regime on the surrounding vertebral bone.

211 Topology and cost optimization applied to develop new designs for a monorail structure

Christopher Carrick, Il Yong Kim

In this study, topology optimization was performed using a design methodology to minimize both the cost and weight of new designs for the skirt support structure of a monorail. Finite element analysis, topology optimization, manufacturing analysis, and a comparative cost analysis were conducted to develop novel lightweight designs. Verification of the designs was done by comparing them against the original structure.
An analysis of the original structure was undertaken: structural analysis was performed using finite element analysis, and a cost breakdown was done based upon provided information by the industrial partner and the cost of the original structure. Manufacturing techniques used to create the original structure were identified.
Topology optimization was performed in several iterations in order to converge on a quality result for the different designs. The large scale of the design space necessitated a new approach for creating detailed results from a large coarse mesh. Multiple loading cases and constraints were accounted for.
The topology optimization results were then used in order to generate manufacturable designs. Different manufacturing methods were analyzed for the best trade-off between representation of the raw optimization result, structural performance, and cost efficiency.
The final step was a cost analysis. The cost analysis was done comparatively to ensure the most qualitative and accurate comparison. The cost of the original structure and its manufacturing methods were used to build and validate the cost model. Features such as the number of parts, joints, bends, and length of cuts were used as metrics for the cost model.

Two new, optimum designs resulted from this study: the first was 55% lighter than the original structure and 54% cheaper to manufacture, and the second was 53% lighter than the original structure and 58% cheaper to manufacture. These results greatly exceeded the initial target of 30% weight savings and 25% cost savings.

212 Topological Design of Vibro-Acoustic Structures using a Generalized Incremental Frequency Method

Niels Olhoff, Jianbin Du

Topology design optimization of vibro-acoustic structures are studied, where the structures are assumed to be subjected to time-harmonic mechanical loading with given amplitude and a prescribed low or high excitation frequency. One of the difficulties of such a problem is that the design often easily converges to a local optimum because the excitation frequency may be located in an interval between two less appropriate consecutive resonance frequencies. In this paper, we seek for a new design strategy of overcoming the weakness of previous methods and deal with the problem in a 'global' and efficient manner. An 'incremental frequency technique' (IF technique) is first presented to show that it is often important to consider different design paths in order to obtain a desirable solution of the vibro-acoustic topology optimization problem. Then, a 'generalized incremental frequency method' (GIF method) based on the IF technique is proposed for any high or low prescribed value of the external excitation frequency. The GIF method provides a way of searching for different local optimized solutions in a systematic manner in different disjointed resonance frequency sub-intervals, and hereby the optimum solution of the problem may be identified from among a small number of obtained candidate local optimum solutions. Numerical examples show that the optimum designs obtained in different resonance frequency intervals normally exhibit different periodicity of structural topology. Numerical tests also show that the 'best' (i.e. optimum) design subject to a prescribed value of the external excitation frequency may not be identified in an interval between two consecutive resonance frequencies that have the same orders as the two resonance frequencies embracing the excitation frequency of the initial design chosen for the topological optimization procedure. The method in this paper may be applied to general vibro-acoustic design problems with multiple disjointed design sub-spaces.

213 Design variables filtering using global sensitivity coefficients in robust design of elastomers for a passenger car

Dooho Lee, Young-Woo Won

The dynamic properties of the elastomers have nonlinear characteristics with respect to displacement as well as frequency – dependent feature, which adds uncertainties to the dynamic characteristics besides its intrinsic material property variations. In elastomer design for vibration damping, an efficient sensitivity analysis method is required considering these uncertainties. In addition, robust design is needed to reduce the magnitude and variability of vibration .

In this study, a global sensitivity analysis procedure was proposed to obtain design information of elastomers in structural systems considering the uncertainties . The global sensitivity method incorporates the random balance design method for variance-based sensitivity information and the FRF-based Substructuring(FBS) method for calculation of vibrational responses, which leads to an very efficient procedure even in complex real structures. In addition, an multi-objective optimization formulation was fulfilled to obtain the optimal design of elastomers that give robust vibration responses. The objective functions were set to the mean and variance of the vibration responses. The Pareto optimal front was calculated using the non-dominated sorting genetic algorithm-II (NSGA-II). For the genetic algorithm little influence design variables were screened using the global sensitivity analysis results for the elastomers, which reduces the number of design variables and also enables us to obtain the Pareto optimal solutions for real complex problems such as passenger cars. These formulations were applied to a passenger car problem to obtain the optimal design of the engine mount systems. The numerical results showed that the newly introduced feature in this study enhanced the calculation performance during the robust optimal design of the elastomers and can be applied successfully to real complex structural problems.

214 Optimum morphing shape design for morphing wing with corrugated structure using RBF network

Gen Nakamura, Kengo Uehara, Nozomu Kogiso, Tomohiro Yokozeki

One of the authors was proposed the morphing wing using corrugated structures [1]. The corrugated structure has deformation flexibility in the corrugation direction, whereas high load bearing capability in the direction perpendicular to the corrugation direction. When the corrugation structure is arranged around the trailing edge, the camber can be changed seamlessly as a plain flap by bending the corrugated structure along the perpendicular direction.

This study considers the morphing shape optimization to maximize the aerodynamic performance such as a lift and lift-to-drag ratio. The airfoil shape is modeled by using NURBS curve and the passing points are treated as design variables. To achieve the morphing shape by arranging the corrugation pattern, the NURBS curve is arranged along to the corrugation structure and connected smoothly to the front side of the airfoil that is fixed as the undeformed shape.

This study adopts the radial basis function (RBF) network as a surrogated optimization method for computational efficiency, because the time-consuming aerodynamic performance is required to evaluate the objective function. In addition, an idea of Tabu search is introduced to make the RBF network efficient.

The RBF network updates the objective function by adding the sample points. The airfoil shape of the design candidate may have waviness curve. Since such an airfoil will fail the aerodynamic analysis, the design candidate is saved as Tabu list without aerodynamic analysis and then the neighboring region is eliminated from the design region as Tabu region. This strategy makes the searching process efficient, especially for searching the feasible designs.

Through numerical calculations, the validity of the optimization method is demonstrated. Then, the optimum airfoil shape along the flapping angle is discussed.

[1] Yokozeki, T. et al., J. Aircraft, 51-3, (2014), pp. 1023-1029.

216 Comprehensive PHEV Powertrain Co-Design Performance Studies using MDSDO

Saeed Azad, Mohammad Behtash, Arian Houshmand, Michael Alexander-Ramos

Plug-in hybrid electric vehicle (PHEV) powertrain design is a complex process that requires an approach which enables the simultaneous integration of component design and powertrain control strategy decisions. Combined optimal design and control (co-design) methods are generally used to support this design paradigm. Although several PHEV powertrain co-design problems have been explored in the past, there have been no studies that have simultaneously addressed the impact of performance criteria such as acceleration performance and all-electric range (AER) along with predefined duty cycles on component design and hybrid mode (non-AER) supervisory control strategies. This is problematic as these performance criteria tend to strongly affect component sizing, which in turn can affect the supervisory control strategy in such a way that a non-performance-based co-design solution may become suboptimal. Therefore, this research addresses these issues by solving a comprehensive PHEV powertrain co-design performance study using a co-design method known as multidisciplinary dynamic system design optimization (MDSDO). In particular, MDSDO is implemented to simultaneously identify the optimal component designs, powertrain supervisory control strategies, and AER performance of a mid-size PHEV during a predefined vehicle duty cycle and a 0-60 mph acceleration maneuver such that the vehicle operating cost is minimized. A family of optimal solutions is generated by performing a parametric study for three distinct values of AER. The results from this study indicate that the formal inclusion of the performance criteria in a co-design problem has a significant impact on both component design and hybrid-mode supervisory control strategies.

217 A new performance prediction method based on a local metamodel built using large data

Kibong Kang, Dong-Hoon Choi

In this study, we propose a new method of performance prediction at a design point generated at an iteration of an optimization algorithm based on a local metamodel built using given large data. Though there are many performance prediction methods using large data such as artificial neural network, boosting, and so on, these methods approximate global trend of performance using the whole large data and usually do not accurately predict the performance at the generated design point. To enhance performance prediction accuracy, we adopt a local metamodeling approach in which we use only data points near to and surrounding the generated design point. Using the clustering method and geometric approach, we devised a novel method of selecting data points among the whole large data with which an accurate local metamodel can be built. The method can be applied without regard to the numbers of the whole data points and design variables. The effectiveness of the proposed method is demonstrated by testing a variety of given data generated using numerical examples and comparing its accuracy with those of existing performance prediction methods using large data.

218 Level set-based topology optimization for a soundproofing acoustic metasurface using Zwicker's loudness model

Yuki Noguchi, Kohei Miyata, Takayuki Yamada, Kazuhiro Izui, Shinji Nishiwaki

We present a level set-based topology optimization method for the design of a soundproofing acoustic metasurface in an acoustic-elastic coupled system.

The perception of acoustic noise strongly depends on a number of human factors. For example, the loudness component of a sound depends on not only sound pressure levels, but also on psychoacoustic effects. Here we design an acoustic metasurface for soundproofing applications that consists of a periodic array of a thin elastic material located within an acoustic medium, based on Zwicker's loudness model. The sound insulating properties of the metasurface are evaluated considering psychoacoustic effects, such as masking effects and the frequency dependence of perceived noisiness. We set specific loudness as an objective functional so that noise transmittance from the acoustic metasurface will be reduced.

Since the acoustic metasurface consists of acoustic and elastic materials, acoustic and elastic waves are coupled at their interfaces. Usual analyses of a coupled system require coupling constraints at the media boundaries, and it complicates the numerical implementation during the topology optimization process. To solve this problem, we introduce a two-phase material model in which the solid and fluid phases are mixed so that the coupled system can be expressed uniformly, and this model is then incorporated in the proposed topology optimization method.

First, we introduce Zwicker's loudness model, used to evaluate acoustic noise, and the two-phase material model that expresses the acoustic-elastic coupled system. The level set-based topology optimization is explained next and we then formulate an optimization problem for the design of a soundproofing acoustic metasurface. Sensitivity analysis is conducted based on the concept of the topological derivative. Finally, two-dimensional numerical examples are given to demonstrate the validity of our proposed method.

219 Surrogate based global optimization using adaptive switching infill sampling criterion

Dohyun Park, In-Bum Chung, Dong-Hoon Choi

A novel switching infill sampling criterion is proposed for a surrogate based global optimization algorithm. In the attempt to reduce the computational burden in global optimization of an expensive black box function, surrogate based global optimization (SBGO) techniques were proposed. The SBGO constructs an initial surrogate then employs an infill sampling criterion (ISC) to sequentially update the model. Previous studies on the ISC involved a fixed weight to emphasize between a global and local search or used a predetermined search pattern. Such ISC's in SBGO may produce results that are easily influenced by the characteristics of a problem. Thus, in this study, we propose an algorithm that adaptively searches globally or locally according to the currently existing sample points to avoid being affected by the aspect of a problem using novel switching conditions. The adaptive ISC was integrated with a weighted minimum distance (WD) metric which encourages the global search to be performed around the existing sample points with smaller function values to improve the convergence rate. The proposed algorithm was tested on ten unconstrained mathematical functions including the Dixon-Szego test functions. The result showed that the novel algorithm outperformed many of the previously established methods and always remained in the top three of low number of function evaluations. For further implementation to constrained problems, auxiliary weight was applied to the WD to repel away from infeasible region when performing a global search. Also, a penalty function was added to the ISC to penalize the violated domain. The results on constrained problems demonstrated comparable results to the COBRA algorithm.

220 Aeroacoustic optimization problem using Lighthill's equation

Ki Hyun Kim, Gil Ho Yoon

In this research, we conducted 2D aeroacoustic optimization problem to reduce the flow-induced noise based on the finite element solution of Lighthill's equation. Acoustic analogy method (for example, Lighthill's equation) is well known for computationally efficient method in aeroacoustic analysis. However, optimization problem using acoustic analogy method has been rarely investigated. Especially, topology optimization research of aeroacoustic problem is not found at all, compared to much research on acoustic topology optimization. Acoustic analogy method is hybrid method solving inhomogeneous acoustic wave equation which is rearranged from compressible Navier-Stokes equation. Left side of acoustic analogy equation describes the wave propagation and right side describes the acoustic source terms. Here, important thing is that flow variables included in source terms are independent of acoustic variables. So, the acoustic source terms are calculated from turbulent velocity field obtained by flow analysis. Among many acoustic analogy equations, Lighthill's equation is first suggested equation with the simplest form. In this research, Lighthill's equation is solved in frequency domain with the assumption of harmonic motion in time. In this case, the left side of Lighthill's equation is just same as the Helmholtz equation. In the flow analysis, stationary incompressible Reynolds averaged Navier-Stokes (RANS) equations with k-epsilon turbulent model are solved using finite element method. And stochastic noise generation and radiation (SNGR) method is used to generate turbulent velocity field from RANS results.

221 Topology optimization of periodic flows using the local-in-time method and the lattice Boltzmann method

Cong Chen, Kentaro Yaji, Takayuki Yamada, Kazuhiro Izui, Shinji Nishiwaki

This research presents a topology optimization method for unsteady incompressible viscous flows using the local-in-time adjoint-based method and the lattice Boltzmann method (LBM). Straightforward global implementations are usually adopted when solving unsteady flow optimization problems. As the adjoint equations are solved backward in time after the flow equations are solved forward in time, these global implementations typically require storage of the entire flow solution history, which may be prohibitive in three-dimensional design optimization problems. In this research, the local-in-time discrete adjoint-based method (LT) is applied to lower the storage requirement. The basic idea of the LT method is to divide the entire time interval into several subintervals. Sensitivity derivatives are then approximated as a combination of local sensitivity derivatives computed for each time subinterval. As a result, only flow solutions for a subinterval need to be stored, which considerably reduces storage cost. The unsteady fluid flow is governed by the Navier-Stokes equations and is calculated here using the lattice Boltzmann method. The proposed method is applied in a pressure drop minimization problem and two- and three-dimensional numerical examples are provided to confirm its validity and utility.

222 Macroscopically isotropic and cubic-isotropic two-material periodic structures constructed by the inverse-homogenization method.

Tomasz Łukasiak

The present paper concerns the 2D problem of the inverse homogenization, i.e. the determination of the microstructure of the periodic composites of given effective properties. The composite structure is made of two elastic and isotropic materials with given bulk and shear moduli (one of which can be a void), the volume fractions being prescribed. The optimization problem is posed on a basic cell Y. The cell is uniformly divided into finite elements. At each element the underlying material is characterized by few independent scalar parameters. These parameters constitute the set of decision variables for the optimization problem.

The objective of this study is to determine the microstructure of the composites with assumed effective isotropic or cubic-isotropic properties. As the underlying material we take: one-parameter material of properties modeled by the SIMP-like methods, 1st rank laminates similar to the Kagome latticed structures 2nd rank laminates.

The optimization problem thus formulated is nonlinear and is solved by Sequential Linear Programming method with a multipoint start. The effective moduli as well as the gradient of the objective function are computed according to the homogenization algorithm for periodic media.
The problem discussed is of vital importance while implementing the optimal material design methods (like the isotropic material design, IMD) in the 3D printing. The material design methods produce only the fields representing the elastic moduli continuously varying in the design domain. The present paper delivers the algorithms to recover the isotropic and cubic-isotropic underlying microstructure. Such kind of structures will be presented as well as variation in plane of microstructure from point to point according to the chosen solutions of the IMD task.

223 Topology optimization design of the box girder based on dynamic characteristics

Heming Zhao, Dongchen Qin, Jiangyi Chen, Qiang Zhu, Zebin Zhang

In order to improve the dynamic performance of the box girder, the optimization of the natural frequency of the structure is performed. Topology optimization is employed for reaching the relevant optimal topological structure in terms of material distribution in the design domain, under the constraint of higher natural frequency with respect to the disturbance frequency. The variable density method is taken to establish the topology optimization model, with the minimum weight being the objective function, displacement and frequency as constraints based on the SIMP (Solid Isotropic Microstructures with Penalization) interpolation model.

While the rectangular element and block element are selected respectively for the surface continuum and the space continuum, the finite element method is used to solve the constrained variables. The efficiency of the code is assessed by calculating and assembling the structural stiffness matrix and the mass matrix in different ways. Considering the generality of the codes, the natural frequency is calculated by the mathematic function integrated in MATLAB. The subspace method and the vector iteration method are also deduced. The optimization results are obtained from an optimizer with certain topological optimality criterion. The application of the density filter, the sensitivity filter and the gray filter are studied for the numerical instability in the process of updating the design variables. The final topology configuration can not only realize the lightweight of structure but also guide the conceptual design. Based on the static topology optimization design, the dynamic topology optimization of the box girder can be performed so that to improve the dynamic performance significantly.

228 An Improved MPP-based Importance Sampling Method for Reliability Analysis

Guijian Tang, Wen Yao, XiaoQian Chen, Yong Zhao

Importance sampling (IS) as an efficient technique in Monte Carlo probability simulation has been widely applied for high reliability system analysis, which can greatly reduce the simulation numbers and improve the efficiency. Among the IS methods, Most Probable point (MPP)-based Importance Sampling Method (MISM) has gained wide attention because of its effectiveness and easy to implement. However, the traditional MISM uses the Acceptance-Rejection (A-R) technique to sample points from the importance regions. The uniform distribution is often set as the suggested function and its value is equal to the value of the point in the Probability Density Function (PDF) where the first-order derivative is zero. This brings efficiency-scarified problems when the derivative exceeds the sampling interval in different dimensional cases. Moreover, in order to increase the efficiency by use of the A-R process, it often performs the variable transformation (e.g. log-transformation). Unfortunately, it doesn't work while the PDF of the random variables is not a log-concave function. In this paper, two feasible strategies were proposed to solve these drawbacks. The first strategy is that the value of the uniform function is set as the maximal value of the PDF, which is obtained by calculating all samples point by point in the target interval. It can be applied to any dimensions as an instructional strategy. The other one is that a well-designed normal distribution function, instead of the uniform distribution function, is used as the suggested function to avoid the variables transformation. Finally, two numerical examples are given to illustrate the effectiveness and accuracy of the proposed method, while a real engineering example is given in the last, which shows the application and the advantages of the proposed method.

229 Bionic sandwich structures design with hybrid core based on topological optimization under multiple constraints

Dong Li, Zhi Sun, Weisheng Zhang, Shanshan Shi, Haoran Chen, Xu Guo

Porous-core sandwich structures with CFRP (Carbon Fiber Reinforced Polymer) face sheets have similar micro structures to biological tissues, for example, grass leaves. However, the

mechanical properties of these sandwich structures are often limited by face-core debonding or core collapse that can significantly affect the integrity of composite sandwich structures. A refined design that could provide higher mechanical properties is desired for light-weight sandwich structures.

The tree leaf, which is much stiffer and larger than grass leaves, has brought new inspiration for the design of core for sandwich structures with CFRP face sheets. Tree veins act similar roles to leaves as honeycomb walls and rigid beams to sandwich structures. An interesting character is that these fractal veins possess different types: the primary veins are thicker in diameter, longer in length, yet relatively less in quantity while the secondary veins are thinner, shorter, yet much more in quantity.

A topological optimization method on the micro structures of core is conducted to achieve higher performances. In the present method, the ground structure method is adopted. By considering local-buckling constraint, embedding-volume and adhesive-area constraint, a bionic hybrid core, which is similar to the fractal distribution of tree veins, is found to be an optimal core design for sandwich structures with CFRP face sheets. In-plane compression experiments indicate that the sandwich structure with hybrid core works better by comparison with sandwich structures with honeycomb core and grid core, respectively.

230 Topology Optimization of Orthotropic Elastic Design Domains with Mortar Contact Conditions

Niclas Strömberg

In this paper we perform topology optimization of orthotropic elastic design domains in unilateral contact with non-matching meshes by adopting the mortar approach. The motivation is 3D printing of assemblies of parts, where the build direction as well as the contact interfaces between the parts strongly will influence the optimal solutions. Thus, topology optimization of a standard isotropic formulation with tied interfaces might not be a proper approach for this kind of design problems. This is studied in this work by maximizing the potential energy of orthotropic linear elastic bodies in unilateral frictionless contact. In such manner, no extra adjoint equation is needed to be solved and non-zero prescribed displacements are also included in the formulation properly. This will not be true if the compliance is minimized. The contact conditions of the non-matching meshes are treated by deriving the mortar integral from the principle of virtual power by representing the normal contact pressure with the trace of the global displacement shape functions. The mortar integral is then approximated with the Lobatto rule using a high number of integration points. In such manner, we obtain a set of Signorini conditions for each non-matching interface which we solve using the augmented Lagrangian approach and Newton's method. The design domains are formulated with orthotropic linear elasticity where intermediate density values are penalized using SIMP or RAMP, and the regularization is obtained by applying sensitivity or density filters following the approaches of Sigmund and Bourdin. The implementation of the methodology is efficient and produces reliable solutions. This is demonstrated for assemblies of design domains in unilateral contact which is rotated with respect to the build direction of a 3D printer.

231 Optimization with Bayesian Network by changing design and epistemic variables

Sangjune Bae, Nam H. Kim, Seung-gyo Jang

In general, a complex engineering system is often composed of many components. In order to determine the performance of the system, it is necessary to understand the functional relationships between components and system. When the reliability of the system is of interest, it is also required to propagate components reliability to the system-level reliability. One way to represent the componentsystem relationship is a Bayesian network, which is also known as a belief network. A Bayesian network represents the probabilistic relationships of a set of components in a hierarchical information graph, which is so-called a directed acyclic graph (DAG). This network is useful to understand how a component probability of failure propagates through the network and how significantly it affects the system probability of failure.

The probability in a Bayesian network is induced from two different sources of uncertainty: aleatory randomness and epistemic uncertainty. Recently, researchers have tried to optimize engineering systems by considering both aleatory randomness and epistemic uncertainty. However, without shaping uncertainty (i.e., reducing uncertainty), reliability-based optimization either cannot satisfy reliability constraint or can yield too conservative design, which may not be practical. This paper shows the effect of controlling epistemic variables on optimization. In particular, the global sensitivity is utilized to find the sensitivity of epistemic variables.

232 Probability-Based Damage Detection of Structures Using Surrogate Model and Enhanced Ideal Gas Molecular Movement Algorithm

Mohammad Reza Ghasemi, Ramin Ghiasi, Hesam Varaee

Surrogate models have received increasing attention to be used in detecting damage of structures based on vibration modal parameters. However, uncertainties existing in the measured vibration data may lead to false or unreliable output results from such models. In this study, an efficient approach based on Monte Carlo simulation is proposed to take into account the effect of uncertainties in developing a surrogate model. The probability of damage existence (PDE) is calculated based on the probability density function of the existence of undamaged and damaged states. The Cascade Feed Forward Neural Network (CFNN) chosen as a meta-modeling technique. Enhanced version of the Ideal gas molecular movement (EIGMM) algorithm is used as the main algorithm for model updating.

The developed approach is applied to detect simulated damage in numerical models of a 72-bar space truss and a 120-bar dome truss. The simulation results show that the proposed method can perform well in probability-based damage detection of structures with less computational effort compared to direct finite element model.

233 An evolution-gradient based hybrid reliability analysis method by MOEA/D and ACC

Gang Li, Bin Li, Hao Hu

The first-order reliability method (FORM) is widely used in structural reliability analysis for its simplicity and efficiency, which is to find the most probable point (MPP) in the standard normal space by solving a single objective optimization problem . The HL-RF algorithm and some improved versions are popular gradient-based algorithms with good convergence and efficiency for weakly nonlinear performance functions. However, they may fail to converge for strongly nonlinear performance functions.
Since the reliability analysis by FORM could be considered as the special case of the multi-objective optimization formulation, denoted as (u,—G—), the multi-objective evolutionary algorithm (MOEA) is a robust alternative for the reliability analysis. However, MOEA needs large amount of function evaluations to obtain the MPP, even for the most outstanding multi-objective evolutionary algorithms MOEA/D.
In this paper, an efficient and robust reliability analysis method (MOEA/D-ACC) is proposed by integrating MOEA/D and the inverse reliability analysis algorithm of the adaptive chaos control (ACC) method, in which the strategy of multi-level search is the key point of the proposed method. Firstly, MOEA/D is used to obtain a rough approximation of Pareto front tail in a wide range of the search space, based on which MOEA/D is then used again to obtain a fine approximation of Pareto front tail in a narrow range of the search space. Finally, the precise location of MPP is determined based on the ACC algorithm. Furthermore, the improved version of ACC (iACC) is presented by improving the updating strategy of the chaos control factor, and MOEA/D-iACC is proposed. Results of the numerical examples show that the proposed MOEA/D-iACC has the best convergence and efficiency among the aforementioned reliability analysis methods.

234 Shape optimization for microstructure design of porous materials described by the Biot model in the homogenization framework

Eduard Rohan, Daniel Huebner, Vladimir Lukes, Michael Stingl

The paper deals with shape optimization of microstructures generating porous locally periodic materials saturated by viscous fluids. This topic is challenging in the context of new material design with obvious applications in many fields of engineering. The aim is to design locally optimal structures according to criteria related to the effective material properties.

The porous material is described as the Biot continuum derived by the homogenization of two decoupled problems: 1) deformation of a porous solid saturated by a slightly compressible static fluid and 2) Stokes flow through the rigid porous structure. The effective medium properties are given by the drained skeleton elasticity, the Biot stress coupling, the Biot compressibility coefficients, and by the hydraulic permeability of the Darcy flow model. These are computed using characteristic responses - solutions of the state problems defined in the representative unit cell constituted by an elastic skeleton and by a fluid channel generating the porosity. The design of the channel is described by the B-spline box which embeds the whole representative cell. The sensitivity analysis for all the homogenized material coefficients is derived using the domain method of the design velocity approach.

In this study we consider two criteria of optimal poroelastic material. In both cases, we require that the permeability is sufficiently large compared to a given threshold, whereby anisotropy can be enforced according chosen preferential directions. As the first problem, we aim to maximize stiffness of the drained porous material and allow for a sufficient permeability. The second problem involves all the Biot model coefficients: the objective is to minimize the undrained material compliance. Issues of the spline box parametrization, the channel shape regularity and FE mesh updates are discussed. The minimization problems are solved using the sparse nonlinear optimizer SNOPT.

235 Design of Adsorbed Natural Gas Tanks with Metallic Inclusions by Topology Optimisation

Ricardo Amigo, Robert Hewson, Emilio Silva

Adsorbed Natural Gas (ANG) tanks are constituted by porous materials able to store gas at high density and low pressure through the adsorption phenomenon, in which gas molecules accumulate on the surface of micro-pores. Adsorption is an exothermic reaction and the adsorption capacity of a material decreases with temperature increase. Since adsorbent materials present poor thermal conductivity, the efficiency of the thermal management determines the feasibility of an ANG tank. This work presents the implementation of the Topology Optimisation Method (TOM) for designing ANG tanks aiming to improve the heat exchange for more efficient adsorption and desorption cycles. This is achieved by the optimal placement of aluminium throughout the activated carbon adsorbent bed aiming the maximisation of the total mass of gas adsorbed by the end of the filling cycle and the minimisation of residual mass after the emptying cycle. The TOM is performed adopting the Solid Isotropic Material Model with Penalisation (SIMP) and a term for the regularisation of the design variables in the objective functions. Resulting topologies for different design domains are presented and compared to the respective homogeneous cases.

236 Topology optimization of structures with elasto-plastic strain-hardening material modeling

Mengxiao Li, Hexin Zhang, Simon,Ho Fai Wong

The objective of this paper is to investigate the influence on the optimized topologies by incorporating the elasto-plastic material model with various yield criterion and different strain-hardening into the density-based topology optimization procedure. Since the increasing requirements in some specific applications, the ideal material assumption of elasto-perfectly-plastic is no longer adequate to obtain a satisfactory solution. In this study, three different modes of strain-hardening are considered: isotropic, kinematic and combined hardening. Also, two types of yield criterion are applied to incorporate with the strain hardening model: Von-Mises and Drucker-Prager yield criterion. The interpolations of the elastic and the plastic response are achieved by applying dependency on the design variable to both elastic modulus and yield function. And the path-dependent adjoint sensitivity analysis is performed to obtain the sensitivities for the elasto-plastic model. The capability of the proposed optimization framework is presented through an example. From the results, it can be concluded that opposite to the post yielding behavior of strain-hardening slightly affect the resulting topologies, the type of yield criterion chosen for the material modeling and the magnitude of the prescribed displacement applied to the structure have a significant influence on the optimized layout.

237 TOPOLOGY OPTIMIZATION AT THE FIRST HALF OF THE 20. CENTURY

János Lógó

It is widely known in topology optimization that the first publication is the paper of Michell in 1904. The reality is that he generalized Maxwell's work published in 1890. Also there are significant papers on the optimality criteria method what are fundamental starting point of this research field. Wasiutynski [1] formulated first in 1939 the minimum-potential criterion what plays primary importance in this field. The optimization community has almost no knowledge about the publications in topology optimization at the 50s of the past century. At this time at the Cambridge University a group of researcher (Foulkes, Cox, Hemp) published significant results what are generally not known. The design was elaborated in elastic or plastic ways and the optimized structures were trusses at the early period although this object was called frame structure. The classical solutions of the different type of plate or shell problems can be followed by the works of Mroz, Prager, Shield.
This state of art presentation will overview in detailed these "hidden" results after Hemp [2].
The following parts will be presented:
A: the minimum-potential criterion of Wasiutynski,
B: basic elements of topology optimization:
1. one can see what kind of results of Maxwell were published and generalized;
2.what types of developments were elaborated in 2D. Lines of principal strains. Conditions of Equilibrium. Special solutions.
3.Michell type theorem for plates and developments. Constant stress solutions. Alternative approaches.
This paper will overview these almost forgotten results and put an end to have no information about the developments in topology optimization. It will be also presented analytical solutions of selected problems and the non-uniqueness of the optimal solutions.

238 Benchmarking approaches for the multidisciplinary analysis of complex systems using a Taylor series-based scalable problem

Shamsheer Chauhan, John Hwang, Joaquim Martins

In the practical use of multidisciplinary design optimization, the prevalent approach for the multidisciplinary analyses (MDA) is nonlinear block Gauss–Seidel iteration, which consists in solving each discipline in a sequential manner, and repeating this sequence until convergence. This approach is easy to implement but often exhibits slow convergence rates or does not converge at all. An alternative is to use approaches based on Newton's method to solve the coupled system, also known as tightly coupled or monolithic approaches. Past work, especially in the field of fluid-structure interaction, shows that Newton-based tightly coupled approaches can be more efficient and robust than loosely coupled approaches for the analyses of coupled systems. With the computing power and methods currently available, it is expected that the application of MDA and MDO to systems of greater complexity in terms of coupling and number of disciplines will increase. This makes it important to compare loosely and tightly coupled approaches for complex systems. To address the lack of literature providing such comparisons, we use a novel and highly flexible Taylor series-based analytical scalable problem with OpenMDAO—an open-source framework for MDA and MDO—to compare coupled Newton and nonlinear block Gauss–Seidel approaches for complex systems. We find that assembly time of the linear systems involved, linear solver efficiency, and strength of coupling in the problem play a major role in determining which approach is more efficient for a given problem. We also observe that the coupled Newton approaches are more robust and scale better than the nonlinear block Gauss–Seidel approaches as the strength of coupling between components increases.

239 Design of micro-structures using methods from shape optimisation

Wojciech Kijanski, Franz-Joseph Barthold

Structural optimisation has a long tradition and has been investigated for many years. The significant increase of possible fields of applications as well as in the considerable number of several real world problems justifies its eminent importance. Besides the mathematical algorithms, sensitivity analysis is a fundamental topic within gradient based optimisation methods. Its realisation is responsible for the efficiency and accuracy of used methods. In this context several works conclude that performing sensitivity analysis using variational methods is the most promising approach [1]. The resulting gradients contain sensitivity information about the given overall mechanical system and can be used for further purposes. For instance, it is possible to extract the sensitivity information for physical reaction forces in terms of nonlinear hyper-elastic problem formulations and to use this information for the design of support areas of mechanical systems by controlling the amplitude of arising reaction forces on single scales.

The principal investigations and ideas for the sensitivity analysis of reaction forces can be transferred to optimisation problems on multiple scales in order to use it to design micro-structures. The essential steps will be outlined and accentuated by some illustrative examples. Consequently the combination of methods for shape optimisation with different established approaches for analysis and simulation of complex heterogeneous materials on multiple scales based on numerical homogenisation techniques [2] opens a remarkable range of applications introducing design variables, objective functions and constraints on different scales.

[1] Barthold et al. Efficient variational design sensitivity analysis. In Mathematical Modeling and Optimization of Complex Structures, Springer (2016).

[2] Miehe, Bayreuther. On multiscale FE analyses of heterogeneous structures: from homogenization to multigrid solvers. Numerical Methods in Engineering (2007).

240 Assessment of filter properties and the numerical treatment in context of Vertex Morphing.

Armin Geiser, Daniel Baumgärtner, Roland Wüchner, Kai-Uwe Bletzinger

In context of shape optimisation, node-based methods like the Vertex Morphing method have shown great potential, especially because of the rich design space and a minimal modelling effort. The Vertex Morphing method has been successfully applied to several problems of industrial size. Nevertheless, recent experiences with practical problems, with highly irregular meshes already in the initial configuration, have shown that more detailed investigations with respect to the filter choice and the numerical properties are necessary.

The core idea of the Vertex Morphing method is a design control field that is defined on the discretized geometry for the numerical analysis. The shape change is described via a convolution integral of the change of the design control field with a filter function. The radius of the filter function is a single design handle that controls the wave length of the optimised shape. The original presentation of the Vertex Morphing method proposes the solution of the convolution integral with trapezoidal integration rule for regular meshes. Within this contribution an alternative numerical method for the solution of the convolution is assessed with respect to accuracy and efficiency and the effect on the shape evolution, especially for irregular meshes. This approach promises to remedy issues introduced by the highly irregular grid sizes of some technical problems.

This contribution will be enriched by different prototypic test cases which isolate individual effects of the filter properties, like edge effects and feature preservation, as well as examples of industrial scale will be given.

242 Gradient-Based Multi-Component Topology Optimization of Sheet Metal Structures with Stamping Die Cost Manufacturing Constraint

Yuqing Zhou, Kazuhiro Saitou

This paper presents a continuous relaxation of our previous work on the multi-component topology optimization in continuum domains [Yildiz and Saitou, 2011, Guirguis et al., 2014], which enables the use of an efficient gradient-based algorithm to attain the simultaneous optimization of a base structural topology and its decomposition. In addition to the fictitious material density used in the classic SIMP method, a new design variable specifying fractional membership to each component is introduced to each finite element, in order to relax the process of decomposing a candidate structural topology into a discrete number of components during the optimization process. The concept of joint stiffness is also relaxed using the new component membership variables. Considering stamped sheet metal structures jointed by resistance spot-welding, the stamping die cost consists of die-set material cost and die machining cost. The former is modeled as the minimum bounding box area enclosing each component, approximated by a product of weighted variances in major and minor directions obtained by a weighted principal component analysis. The latter is modeled as an empirical shape complexity index similar to the one available in the literature [Boothroyd et al., 1994]. Examples on compliance minimization of multi-component sheet metal structures are presented, where the proposed continuous relaxation formulation solved by a gradient-based optimization algorithm generated comparable results with dramatically improved computational efficiency over our previous results by the discrete formulation solved by a genetic algorithm.

244 Challenges in implementing topology optimization to established commercial software

David Weinberg, Nam H. Kim

This paper discusses several challenges in implementing topology optimization in the commercial-level finite element analysis software. The first challenge is the interface between the optimization module and analysis module. This presentation will discuss about how to minimize changing the preexisting software architecture, especially when calculating adjoint sensitivity. The second challenge is to support all different types of elements and different types of analyses. If not carefully planned and implemented, it can be equivalent to making multiple versions of the existing FEA software. In addition, topology optimization requires the calculation of adjoint sensitivity which can result in the length of the code being doubled or even quadrupled. Therefore, it is necessary to maximize the use of existing routines and minimize different versions of similar functions. Also, users will need the ability to run different solution types together to achieve a single conformal design. How this was implemented will be discussed in detail. Finally, the last challenge is to extract valuable information from topology optimization results. It is well known that interpreting topology optimization results is not trivial because the results are given in a grey-scale image. It is always challenging how to interpret optimization results for follow-up detailed design and manufacturing. For that purpose, extracting boundary geometry and constructing smoothed and meshable solid geometry (BREP) will also be discussed and demonstrated. The complete process of creating an optimized and conformal design using FEA and subsequent automated smoothed geometry generation and final optimized geometry to meshed and analyzed verification model will be shown.

245 Level set-based topology optimization method for the design of a perfectly absorbing metasurface

Hiroski Takahashi, Takayuki Yamada, Shinji Nishiwaki, Kazuhiro Izui

This paper proposes a level set-based topology optimization method for the design of a perfectly absorbing metasurface. In recent research, advances in the study of surface plasmon phenomena have guided the fabrication of subwavelength plasmonic metasurfaces that can impart abrupt changes to the phase and amplitude of incident light over the deep-subwavelength length scale. Optical resonators have been used for enhanced photodetection, light modulation, and so on. The designs of many of these devices are based on the concept of perfect absorption, the complete absorption of light in the resonators. In recent years, metasurfaces have been used as perfect absorbers because of their characteristics, such as fineness of structural detail and flexibility in the manipulation of light. However, almost all metasurfaces to date have been designed by trial and error, using simple geometrical shapes, hence the need for general design methods that are based on mathematical and physical principles. Therefore, we propose a new topology optimization method, based on mathematical and physical principles, for the design of a metasurface that can lead to complete light absorption in the device. We use a level set-based topology optimization method because it provides clear structural boundaries that have good engineering utility. In this paper, we first explain the level set-based topology optimization method, then formulate the optimization problem for the metasurface design, using a level set boundary expression, and, based on this formulation, construct an optimization algorithm for the design problem. Finally, several numerical examples are provided to confirm the usability and versatility of the proposed method.

246 Multidisciplinary Robust Design Optimization of Generic Fighter Aircraft using Global Variable Fidelity Modeling

Maxim Tyan, Le Viet Thang Nguyen, Nadhie Juliawan, Joon Chung, Sangho Kim, Jae-Woo Lee

A multidisciplinary robust design optimization framework for advanced generic fighter aircraft design is presented in this paper. The developed framework is composed of aerodynamics, weight and balance, propulsion, performance, stability and control, and mission analysis disciplines. The accuracy of the multidisciplinary analysis is enhanced with high-fidelity RANS CFD aerodynamic analysis. The global variable fidelity modeling algorithm manages the use of the high and low fidelity analysis to accurately predict the location of the robust optimum point without significant increase of computational time. The algorithm constructs the global scaling model that describes the error between high and low fidelity analyses and iteratively refines the model near the optimum point. The robust design formulation helps to minimize the influence of deviations caused by uncertain flight conditions on aircraft performance. The iterative strategy for probabilistic analysis of the baseline and robust optimum configuration using reduced number of Monte Carlo Simulations is also proposed. The developed multidisciplinary robust design optimization framework for fighter aircraft design yields a more trustworthy design comparing to traditional deterministic optimization.

247 On the zero stress concentration design of notched structure in pyrotechnic separation device

Bo Wang, YunFeng Shi, Rui Li

Notched structures are most seen in pyrotechnic device of aerospace vehicles. Due to the special functional requirements, an ideal notched structure within pyrotechnic device shall perform a large SCF under bending and small SCF under tension, which makes the design of notched structure a great challenge. In this paper, an optimized notched structural configuration is presented which can efficiently reduce its tensile SCF without changing its bending SCF: by the new design of loading end of notched structure, the eccentricity of the eccentric tensile load become designable, then through parameter optimization method the optimal structure whose neutral layer passes exactly through the notch root can be obtained. The optimal structure shows almost zero tensile SCF at its notch root while its bending SCF remain unchanged. Further discussion reveals the mechanism of zero SCF at notch root and gives the necessary condition for notched structure to achieve zero SCF.

248 Satisfying stress constraints in density based topology optimization by length scale control

Oded Amir, Boyan Lazarov

Despite many research efforts that resulted in a variety of computational approaches, satisfying stress constraints in continuum topology optimization is still a challenge. Their local nature requires either to consider a large number of constraints or to resort to approximate aggregation techniques.

In the current work, we focus on the relation between the length scale imposed on the topological layout and the magnitude of the extreme stresses. We show that an increase in length scale leads to a monotonic reduction in the maximum stresses. Increasing the length scale of the solid phase leads to a reduction in stresses due to the resizing of critical members. Similarly, increasing the length scale of the void phase leads to a relaxation of stress concentrations on the edges of holes due to the reduction of curvatures. Based on these observations, we treat the parameters that control length scale in the context of the robust density-based formulation - namely filter radius and projection thresholds - as design variables.

We propose a computational procedure in which the length scale parameters are updated in an outer optimization loop according to the sensitivities of the maximum stress. In the inner optimization problem, global quantities such as weight, displacement and compliance are optimized in a standard approach. Furthermore, we introduce a spatially varying length scale such that local stress violations can be treated effectively without significant compromise on global performances, such as displacement and compliance. Preliminary results demonstrate the capability to generate topological designs that satisfy the stress limit without actually imposing neither local nor aggregated stress constraints. This opens up new opportunities for developing efficient procedures for large-scale topology optimization with stress constraints.

249 Design and Progressive Damage Analysis of Variable Stiffness Composite Laminates Based on Three-dimensional Hashin Failure Criterion

Yan Zhang, Pengfei Wang, Bingyang Li, Yingze Cao, Fenfen Xiong

With the development of Automatic Tow Placement machine in past years, it is able to place steered fiber tows in plane. Due to the variation of properties along their surface, such structures are termed as variable stiffness composite laminates. The objective of this paper is to study the progressive damage process of variable stiffness composite laminates with given geometry and material properties under tensile loading. Eight different schemes for the fiber laying of variable stiffness composite laminates are proposed in this paper. Meanwhile, four groups of constant stiffness composite laminates with straight fiber are studied as the baseline cases. A user-developed continuum damage model based on the three-dimensional Hashin criterion is implemented in the finite element analysis platform ABAQUS to carry out the simulation of damage initiation and material stiffness degradation. In order to correctly predict the progressive damage process of variable stiffness composite laminates under tension, it is of crucial importance to take into account the different failure modes. The load-carrying capability of variable stiffness laminate is about 18% higher than the corresponding laminate with straight fiber. Compared to the traditional straight-fiber composite laminates, the variable stiffness composite laminates can achieve better load redistribution and then result in great improvements of the structural performance, due to flexible and reasonable design of the stacking sequence and path of the curvilinear fiber.

250 Topology optimization of general-joint planar linkage mechanisms with an application to finger rehabilitation device design

Seok Won Kang, Jeong Han Yu, Sang Min Han, Yoon Young Kim

Although topology optimization methods can inspire designers, their use for the design of linkage mechanisms is not yet fully developed. However, there are a number of new mechanism design problems, as in robots or robotic rehabilitation devices. One of the critical limitations of earlier linkage mechanism synthesis methods by gradient-based topology optimization is that mechanisms only with one type of joint, a revolute joint, can be synthesized. The handling of revolute joints alone limits the capability of topology optimization considerably, and some mechanisms involving prismatic joints cannot therefore be synthesized. Here, we aim to develop a topology optimization method that can synthesize mechanisms with general joints including revolute and prismatic joints. The specific application in mind is the topology-optimization-based design of several robotic rehabilitation mechanisms. To this end, we propose a new ground model termed the joint element connected rigid-block model (JBM). The key idea of the proposed JBM is that the existence of prismatic joints and revolute joints are directly controlled by design variables. After testing the validity of the developed formulation with the JBM, we applied it to the design of a robotic finger rehabilitation device. An interesting design, not available in the existing literature, was synthesized, and the result may inspire designers in the field. It is expected that this method can be more useful as an inspirational design tool for the robotic industry in the future.

251 Pylon and engine mounts performance driven structural topology optimization

Simone Coniglio, Christian Gogu, Rémi Amargier, Joseph Morlier

Engine deformations during operation are an increasing concern for engine performances. The tip-clearance, defined as the radial gap between blade's tip and engine casing, can show small variations induced by aircraft maneuvers. These variations can produce increased tip leakage flow, secondary flows and vortex losses that can sensibly increase the engine trust specific fuel consumption (TSFC). In this paper the impact of pylon and nacelle design parameters on in-operation engine performance and overall mass is investigated for a turbofan engine. The structural behavior of the integrated engine will be simulated thanks to a linear finite element model that repoduces the mechanical behavior of the engine under different load cases. Both rotor and stator are modelled to evaluate tip clearance defarmations at different engine stages. In a first order approach these engine deformations are evaluated as the difference of radial displacements of initially superposed points of rotor and stator relative to the blade's tip. Then an in house performance engine model evaluates thrust specific consumption as a function of the tip clearances.

In a first coarse approach a parametric optimization study is implemented to find pylon thrust link optimal positions, orientations and length. TSFC sensitivity analysis are analytically computed in order to use gradient base optimization algorithms. Then a recently developed exokicit topology optimization approach, called Moving Node Approach (MNA), is evaluated with TSFC as objective on a small region between pylon and engine casing. A comparison is done with the parametric approach (at overall iso-mass). The ralationship between classic compliance driven topology optimization and TSFC driven topology optimization is also analyzed.

252 Material Optimization in Transverse Electromagnetic Applications

Johannes Semmler, Lukas Pflug, Michael Stingl

We discuss a class of algorithms for the solution of discrete material optimization problems in electromagnetic applications. In this physical setting, we characterize a material by its relative permittivity which is assumed to be a complex-valued symmetric tensor. Furthermore, the set of admissible materials is given by a graph-like structure connecting given material tensors by an appropriate parametrization on each edge. The algorithmic idea is based on the sequential convex programming idea, however, in each major iteration a model is established on the basis of the material tensor. The resulting nonlinear parametrization is treated on the level of the sub-problem, for which, due to block separability of the model, globally optimal solutions can be computed. Although global optimization of non-convex design problems is in general prohibitive, a smart combination of analytic solutions along with standard global optimization techniques leads to a very efficient algorithm for the most relevant material parametrizations. The effectiveness of the algorithm in terms of computation time as well as quality of the solution is demonstrated by a series of numerical examples ranging from the optimal design of anisotropic cloaking layers for nano-particles to the identification of multiple materials in a matrix by an inverse problem.

253 Optimization of heat exchangers

Mate Petrik, Karoly Jarmai

Heat exchangers are used in industrial and household processes to recover heat between two process fluids. This paper reports numerical investigations on heat transfer in a double pipe heat exchanger. The working fluids are water, and the inner and outer tube was made from structural steel. There are several constructions which able to transfer the necessary heat, but there is only one geometry which has the lowest cost. This cost comes from the material cost, the fabrication cost and the operation cost. These costs depend on the material types and different geometric sizes, for example inner pipe diameter, outer pipe diameter, length of the tube. The performance of the heat exchanger and the pressure drop are in a close interaction to the geometric sizes. Optimum sizes can be calculated from the initial conditions (when one of the process fluid inlet and outlet temperature and the flow rate is specified). The correlations to the Nusselt number and the friction data come from experimental studies. The optimization is made using the generalized reduced gradient method.

254 Life cycle assessment of welded structures using cost optimization

Karoly Jarmai

The main requirements of a modern load-carrying structure are the safety, fitness for production and economy. The safety and producibility are guaranteed by design and fabrication constraints, and economy can be achieved by minimization of a cost function.
The cost plays an important role in the design of engineering structures. In the case of welded structures the cost comparison helps to select the most economic structural version since welding is an expensive fabrication technology. Our research has been focused on the use of the optimum design methods to minimize the cost of welded structures such as beams, tubular trusses, portal frames, stiffened plates and shells, crane girders, press frames, etc.
These cost calculations are founded on material costs and those fabrication costs, which have a direct effect on the sizes, dimensions or shape of the structure. The cost function includes the cost of material, assembly, welding as well as surface preparation, painting and cutting, edge grinding, forming the shell and is formulated according to the fabrication sequence. Sometimes we can predict the cost of design and inspection, but usually they are proportional to the weight of the structure. Cost and production time data come from different companies from all over the world. When we compare the same design at different countries, we should consider the differences between labour costs. It has the largest impact on the structure, if the technology is the same. When we consider life cycle assessment, the repair, the maintenance, and the disposal or recycling costs are also important.
In this paper, we describe the new cost calculations of the different technologies, considering some newer welding and cutting technologies like laser, plasma, waterjet, etc.
On welded beam and welded stiffened plate examples we show the cost distributions at the optima. The generalized reduced gradient and the particle swarm optimization techniques are used.

255 A model of layer by layer mechanical constraint for additive manufacturing in shape and topology optimization

Grégoire Allaire, Charles Dapogny, Alexis Faure, Georgios Michailidis

The purpose of this work is to introduce a new functional of the domain, to be used in shape and topology optimization problems as a means to enforce the manufacturaility of structures by addive manufacturing process. Purely geometrical constraints, like thickness or angle-base criteria, are not enough and one should resort to more involved criteria. We propose one such functional which aggregates the self-weights of all the intermediate stuctures of the shape appearing in the course of its layer by layer assembly.

Its mathematical analysis is performed. In particular, computing its shpe derivative is not standard since usual perturbations of the final, completed, structure induce non-classical perturbations of the intermediate shapes which occur during the build process. Typically the upper flat boundaries of the shapes under consctruction are not allowed to move. Nevertheless we exhibit a specific subclass of perturbations which allows us to compute a shape derivative by means of an adjoint approach.

It turns out that this class of constraint functional is very costly to evaluate, due to the large number of successive layers required to build the final shape (each of them requiring a finite element analysis). Therefore, we propose an interpolation algorithm, the goal of which is to significantly accelerate the computational effort.

The main idea is to build a piecewise affine approximation of the cost function and of its shape derivative by using the derivative of the elastic displacement with respect to the height of the intermediate structure (this is another application of the concept of shape derivative). Eventually, a numerical validation and some concrete examples are discussed.

256 Gradient based structural optimization of a stringer stiffened composite wing box with variable stringer orientation

Sascha Dähne, Christian Hühne

The structural optimization plays a key role in multidisciplinary optimization. The proof of structural integrity is a prerequisite for the performance assessment of a wing design. In addition, the modification of the structural design allows changing the bend-twist coupling properties in a beneficial way for overall cruise performance.
Due to the high number of design variables affecting the mass and stiffness of a wing box, a gradient based process is established. It meets the needs of fast convergence and enables the coupling with aerodynamic analyses that provide gradients as well.
A well suited parametrization of the design variables is necessary, especially for composite materials. Therefore, lamination parameters are used, which are proven to be suitable for gradient based optimization. In order to consider stiffening structures (i.e. stringer on the wing cover), a smeared stiffener approach is used. With this approach, it is not necessary to model the stringer explicitly in the Finite Element model. The influence of different stringer shapes and their orientation can be evaluated with the method suggested in this paper. In order to reduce calculation time, the numerical model is evaluated using analytic formulations for global and local stability as well as strength.
The two approaches, smearing the stiffeners or explicitly modeling stiffeners, are validated by comparison of global deformations. The optimization process is applied to a representative wing box loaded with an eccentric load. The influence of different stringer orientations on the structural deformation is examined in conjunction with the optimization of lamination parameters.

258 A discrete particle swarm algorithm for sizing optimization of steel truss structures

Waldir N. Felippe, Luiza F. Carneiro

Traditionally, the algorithms to solve structural engineering optimization problems consider that the design variables are continuously valued. However, in steel structural design practice, some variables are chosen from discrete sets of steel profiles during the sizing process of structural elements to avoid extra costs associated with the use of non-standard section sizes. Despite of that, there is an extensive bibliography concerning continuous valued design variables and particle swarm optimization (PSO) algorithms. On the other hand, smaller attention has been paid to solve problems with discrete valued design variables with PSO algorithm support. In this paper, a discrete particle swarm algorithm is presented and applied in some benchmark problems. An actual truss optimization problem is also presented and displacement and tensions constraints are considered in accordance with Eurocode 3.

259 Young's modulus control in material and topology optimization

Grzegorz Dzierżanowski, Tomasz Lewiński

We discuss compliance minimization from the broad perspective of Free Material Design (FMD). Our approach differs from the standard one by choice of the design variable; we use k-Youngs modulus in place of Hookes tensor, depending on the direction k in physical space. This space is two-, or three-dimensional, depending on mechanical problem considered. We refer to thus defined optimization problem as to Youngs modulus design (YMD). Motivation behind our research derives mainly from an interest in optimizing these elastic moduli which tightly correspond to principal stresses at each point in the design space.
Since the compliance is equivalent to the lowest value of the functional of total stored energy expressed in stresses, the optimization task under study takes a form of the following constrained variational problem. Fix two variables for which the total stored energy functional is minimal: (i) design variable the directional k-Young modulus field restricted by an isoperimetric condition, also referred to as cost function, and (ii) state variable the statically admissible stress field. The cost function in (i) replaces trace constraint known from the FMD formulation while retaining all of its properties. Here we just mention that the YMD isoperimetric condition is isotropic as it is expressed in terms of invariants of k-Youngs modulus function E(k).
Similarly to the stress-based FMD, the YMD problem also reduces to minimizing a functional of linear growth in stresses. Consequently, optimal stress fields may identically vanish in subdomains of positive measure in the design area. If this is the case then optimal material in these subdomains degenerates to void, hence a hole is created and YMD becomes the topology optimization problem. A characteristic feature of YMD is that the functional to be minimized is Michell-like, i.e. it takes a form of an integral expressed in terms of absolute values of principal stresses.

260 Designing metamaterials for enhanced noise and vibration properties

Lise Noël, Claus Claeys, Elke Deckers, Wim Desmet

Nowadays, ecological trends and stringent requirements increase the demand for highly efficient components and structures. Lightweight designs, with high stiffness to mass ratios, are appealing as they offer enhanced mechanical behavior at a lower weight. However, they exhibit poor noise and vibration attenuation performance. Recently, vibro-acoustic metamaterials were developed to combine good mechanical properties with favorable noise and vibration ones.
Metamaterials use the concept of resonant additions to create so-called band gaps, i.e frequency ranges where no free wave propagation is possible. Contrary to band gaps based on Bragg scattering in phononic crystals, resonant metamaterials do not require a periodic grid of inclusions with a characteristic length in the same order of magnitude as the wavelength to

be attenuated. Therefore, they can be designed and manufactured to be light and compact while exhibiting noise and vibration insulation at low frequencies.

Band gap frequencies in metamaterials are driven by the resonance frequency of the added resonators. Assuming an infinite periodic grid of resonant additions, the dispersion properties and thus the band gap frequencies can be predicted through unit cell modeling and the application of Bloch-Floquet boundary conditions. So far, the design and fine-tuning of these innovative materials remain largely based on iterative trial and error procedures.

A density based topology optimization approach is proposed to tackle the automatic design of such metamaterials. Working with periodic infinite structures, the dispersion properties and band gap frequencies are evaluated by exploiting a unit cell modeling approach. Single material layouts are considered and optimization problems are solved resorting to gradient based algorithms. To improve noise and vibration properties, several objectives are pursued. In particular, maximum band gap width is considered to achieve large frequency range of vibration attenuation.

261 Optimum structural design for high-precision space smart reflector

Nozomu Kogiso, Naoya Furutani, Tomohiko Naka, Kimihiro Kimura, Hiroaki Tanaka, Takashi Iwasa

One design candidate to resolve such severe design requirements is a smart structural system which the structural shape is actively controlled by actuators. One of the authors has proposed a smart sub-reflector system for radio astronomical satellite mission [1]. The primary reflector is planned to have 3 m aperture consisting of six identical panels, and each is connected to the back-up structure through three kinematic couplings to avoid the surface shape distortion. The smart structure is arranged in the sub-reflector with 0.3 m aperture, where surface adjustment actuators are allocated and each consists of a piezoelectric stack actuator and a displacement magnifying mechanism.

This study concerns the optimal designs of primary components of the smart sub-reflector system. One is the optimal actuator layout design to adjust the surface error of the primary reflector. The actuator will deform the sub-reflector surface shape to correct the path length errors due to the shape distortion of the primary reflector. The optimum actuator layout design problem is formulated to maximize the antenna gain for the distorted primary reflector and solved by using a covariance matrix adaptation evolution strategy (CMA-ES). Several design solutions are introduced as design examples.

The second is the optimum shape design of the displacement magnifying mechanism that is required to compensate the required displacement transformed from the actuator force. The mechanism is designed as a kind of compliant mechanism to improve the reliability by reducing the number of small fastening portions that causes the backlash or friction. The optimum shape is obtained to maximize the output displacement subjected to the stress, natural frequency and the buckling load. Several experimental results for the manufactured optimum mechanism are shown to verify the optimization.

[1] Tanaka, H., et al., J. Intel. Mat. Sys. Struct., 27-6, (2016), 764-773.

262 Optimum design of compliant mechanism for morphing wing structure using level set-based topology optimization

Akari Tsuda, Nozomu Kogiso, Masato Tamayama, Takayuki Yamada, Kazuhiro Izui, Shinji Nishiwaki

A wing that can be deformed the geometrical shape seamlessly and continuously to improve aerodynamic performance of wing is called a morphing wing [1]. As the internal structure of the wing to achieve the desirable deformation, a compliant mechanism has been proposed. Most previous studies have adopted the ground structure approach to obtain the internal structural configuration of the morphing devices.

We adopt the level set-based topology optimization method [2] to improve the structural feature of the morphing wing. As the first study, a static deformation is considered for several assumed ideal deformations with different flap angles. The optimization problem is formulated to minimize the difference between the ideal given deformed shape and the deformation of the obtained compliant configuration, where the mean compliance is not directly used. In addition, the aerodynamic reactive force due to deformation is considered by applying an equivalent pressure to the airfoil surface.

Through numerical examples, validity of the proposed problem formulation is evaluated. Then, the effect of the actuator position on the optimal configurations is investigated by changing the applied load point.

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[2] Yamada, T., et al., A topology optimization method based on the level set method incorporating a fictitious interface energy, Comput. Meth. App. Meth. Eng., 199, (2010), 2876-2891

265 Towards additive manufacturing process considerations in stress-constrained topology optimization

Dirk Munro, Can Ayas, Matthijs Langelaar, Fred van Keulen

Structural topology optimization problems are typically cast in a simply-constrained minimum compliance-type formulation, subject to in-service loading conditions. However, with the emergence of complex manufacturing techniques in competitive industrial settings, a need has arisen to optimize the geometry of components and parts with respect to the manufacturing process as well. In order to optimize the geometry with respect to the process, responses and sensitivities have to be calculated with a numerical process simulation (in terms of a material density distribution). The peculiarity with manufacturing process simulations is that the conventional in-service loading condition is absent during the analysis. However, stresses are induced by the incompatibility of design-dependent, nonelastic strains. This is particularly true of metal additive manufacturing (AM) techniques.

In its simplest form, AM process simulations involve a (layer-by-layer) changing structure subject to thermoelastic loading conditions. In other words, two challenges arise: first, the layer-by-layer nature of the manufacturing process necessitates computationally expensive (transient) numerical simulations; and secondly, thermoelastic loading conditions, which cause deformations and stresses in the absence of conventional (external) loads, have to be translated into a coherent and representative formulation. Results from literature will be presented which highlight the issues pertaining to simply-constrained minimum compliance topology optimization of thermoelastic structures, motivating the need for stress-constrained minimum weight formulations. In addition, stress constraints are anticipated to account for failure during AM process. Then, by resorting to a simple but representative textbook example (a mainstay of stress-constrained structural optimization), the implications of AM process considerations in a stress-constrained minimum weight formulation will be presented and discussed.

266 Global Topology Optimization?: Stochastic Level-Set Method

Lester Hedges, H Alicia Kim, Robert Jack

We present a new method for stochastic shape optimisation. The method generalises an existing deterministic scheme, in which the structure is represented and evolved by a level-set method coupled with mathematical programming. The stochastic element of the algorithm is built on the methods of statistical mechanics and is designed so that the system explores a Boltzmann-Gibbs distribution of structures (Hedges et al. 2016). This is coupled with the level set topology optimization method where the stochastic element is added to the Hamilton-Jacobin equation governing the boundary modification. The presentation will discuss the detailed implementation of the method.

Topology optimization is a well-known non-convex problem and the deterministic algorithm can get trapped in local optima: the stochastic generalisation enables sampling of multiple local optima, which aids the search for the globally-optimal structure. Compared with other stochastic optimisation methods that do not use gradient (or sensitivity) information, the scheme presented here has a favourable characteristic; as the noise strength is reduced, it recovers to the standard deterministic method, so it is guaranteed to perform no worse than that method (this property is not guaranteed in many stochastic algorithms). The method is demonstrated for several simple geometrical problems, and a proof-of-principle calculation is shown for a simple engineering structure. The presentation will present an analysis of the numerical investigations and identify future challenges when applied to structural topology optimization.

L. O. Hedges, H. A. Kim, and R. L. Jack, 2016. "Stochastic level-set method for shape optimisation", arXiv:1612.04681.

267 A novel heuristic generator of structural topologies based on sorted compliances

Monika Mazur, Katarzyna Tajs-Zielinska, Bogdan Bochenek

Optimization of structural topology is a constantly developing area. One of the most important issues stimulating this progress is the implementation of efficient and versatile methods to the generation of optimal topologies for engineering structural elements. Among them there are many heuristic algorithms. Heuristic optimization techniques are gaining popularity among researchers because they are easy for numerical implementation, do not require gradient information, and one can easily combine this type of algorithm with any finite element structural analysis code. In this paper a novel algorithm for minimum compliance topology optimization is proposed. The idea of an original heuristic concept is as follows. Based on the results of structural analysis values of local compliances are evaluated for design elements. Next, compliances are sorted in ascending order and subsets of elements of the smallest and of the largest compliance values are selected. For design elements of intermediate compliances values of a specially adapted monotonically increasing function are assigned. Finally the local update rule applied to design element is constructed based on values of the function evaluated for a particular element and for elements forming its specially selected neighborhood. The proposed technique is easy to implement, there are only very few parameters to adjust. The algorithm does not require any additional density filtering and generated topologies are free from the checkerboard effect. What is also important, this technique suits well optimization of both plane and spatial topologies. Selected examples of minimal compliance topologies generation of plane and spatial structures are presented showing effectiveness of proposed approach. It can be concluded that the topology optimization algorithm based on sorted compliances can be considered as a real alternative to other techniques used for generating minimal compliance topologies of engineering structural elements.

268 Generator of Optimal Topologies by Irregular Cellular Automata - GOTICA applied to spatial engineering structures

Katarzyna Tajs-Zielinska, Bogdan Bochenek

For decades topology optimization has been stimulating progress within structural optimization area. Appearance of efficient and versatile optimization algorithms which can be implemented into broad range of engineering applications cause popularity of structural topology optimization in all industry areas. Despite the multiplicity of problem formulations, developed algorithms and increasing range of engineering applications, various aspects of topology optimization are still under consideration. One of the most important problems to cope with is to adjust optimization algorithms abilities to high requirements imposed on effectiveness and reliability of structural analysis tools. For real structural elements when implementation of regular meshes is inadequate for example upon existence of stress concentration regions, a non-uniform density of elements represented by irregular meshes should be used in order to achieve an accurate solution without excessive increase of number of elements. Since structural analysis is often a part of optimization problem therefore irregular mesh problem arises also for performing design process. This paper undertakes this problem and presents the effective heuristic algorithm based on idea of cellular automaton, modified and adapted to cope with non-uniform cubic and tetrahedral lattice of cells. The implementation of non-uniform cells of Cellular Automaton requires a reformulation of standard local rules, provided for regular lattices. This paper proposes therefore new local update rule dedicated to irregular lattices of cells. The rule incorporates influence of cell sizes on update process. The proposed Generator of Optimal Topologies by Irregular Cellular Automata - GOTICA algorithm offers low number of parameters to adjust, fast convergence, easy application to 3D problems and easy implementation into professional FEM analysis codes. Selected examples of minimal compliance spatial topologies generation are presented.

270 Characterization of geometric uncertainty in gas turbine engine components using CMM data

Jennifer Forrester, Andy Keane

Measurements of component geometry are routinely made for inspection during manufacturing. Typically this results in 'clouds' of points or pixels depending upon the measuring system. Examples include points form laser-based or touch-probe co-ordinate measuring machines (CMMs). The point density may vary as will the cost and time taken to make measurements. There can also be gaps and occlusions in data, and sometimes it is only practical to collect sparse sets or points in a single dimension.
This data often provides an untapped source of a quantitative uncertainty information pertaining to manufacturing methods. It is proposed that state-of-the-art uncertainty propagation and robust design optimization approaches, often demonstrated using assumed normal input distributions in existing parameters, can be improved by incorporating these data. Inclusion of this information requires, however, that the point cloud be converted to an appropriate parametric form.
Although the design intent of a component may be described using simple geometric primitives joined with tangency or at vertices, manufactured geometry may not exhibit the same simple form and line and surface segment end locations are notoriously difficult to locate where there is tangency or shallow angles. In this paper we present an approach to first characterise point cloud measurements as curves or surfaces using Kriging, allowing for gaps in data by extension to universal Kriging. We then propose a novel method for the reduction of variables to parameterise curves and surfaces again using Kriging models in order to facilitate practical analysis of performance uncertainty. The techniques are demonstrated by application to a dovetail-type gas turbine engine blade to disc joint where the contact surface shape is measured and the notch stresses are critical to component performance.

271 Topology optimization for fluid-structure-interaction problems

Christian Lundgaard, Joe Alexandersen, Casper Schousboe Andreasen, Mingdong Zhou, Ole Sigmund

This study concerns the application of the density-based topology optimization (TO) method for fluid-structure-interaction (FSI) problems. The Navier-Cauchy and Navier-Stokes equations are discretised using the finite element (FE) method and solved in a monoltihic formulation. The physical modelling is limited to two dimensions, steady state, a stationary mesh (i.e. the deformation gradients are assumed negligible) and constant structural and fluid dynamic properties. The optimization sensitivities are computed with the discrete adjoint method, and the optimization problems are solved using the Method of Moving Asymptotes (MMA). The optimization problem is set up in the well known robust formulation, and it is demonstrated that the robust formulation may ensure smooth and crisp 0/1 final designs, and may make the optimization problem less sensitive to the choice of interpolation functions, model parameters and penalization and continuation strategies. Non-physical floating islands consisting of solid elements may be removed in some optimization problems by combining different objective functions in a Pareto optimal formulation. The FSI TO framework is tested for low and moderate Reynold numbers on problems similar to previous work in the literature and two new flow mechanism problems. The optimized designs are consistent with respect to benchmark examples, and the FSI coupling is clearly captured and illustrated in the optimized designs.

272 Fully coupled topology optimization of flexible multibody systems with constraints

Alexander Held, Thomas Kohlsche, Robert Seifried

In the last years considerable progress has been made in the dynamical topology optimization of compliant mechanisms, which undergo large working motions. On the one hand, a variety of methods for the efficient and precise modeling of flexible multibody systems has established as, for instance, nonlinear finite element methods or the floating frame of reference approach. On the other hand, optimization procedures have been studied and presented in which the structure of the flexible components are best adapted to the dynamical loads. They can be roughly divided into weakly and fully coupled methods.
Weakly coupled methods rely on the definition of equivalent static loads, and the iterative solution of static subproblems. Fully coupled methods, in contrast, take the whole dynamic behavior of the system within the simulation period into account and are in the focus of this work. In the fully coupled approach scalar objective functions are often obtained from the time simulation results using integral-type objective functions. In addition, the problem formulation often contains pointwise constraints to define, for instance, maximum permissible stresses or deformations. These are not trivial to consider in the solution of the optimization problem. Hence, in this work two different strategies are tested to include pointwise constraints in the optimization of dynamically loaded flexible multibody systems. Both methods allow to use an adjoint approach for the gradient computation. On the one hand, the pointwise constraints are transformed into integral-type equality constraints. On the other hand, the constraints are aggregated using the Kreisselmeier-Steinhausen function. The approaches are tested using the example of a constrained topology optimization of a flexible slider-crank mechanism.

273 Topology Optimization and Reinforcement Derivation Method (RDM©) of a Hybrid Material Sump

Marine Favre Decloux, Alex Desmond, Lucy Fusco, Martin Gambling, Markus Hose

This project aims to demonstrate how the power of various optimization methods, when coupled with experienced design engineers, can deliver weight savings and performance improvements. Topology optimization methods were applied to develop a new lightweight hybrid material sump, whilst achieving the same stiffness and stress requirements as the baseline aluminium sump casting.
The optimization study explored three design options with various levels of differential integration into the sump casing, each generating different package spaces. Topology optimization in Genesis was applied to three options while keeping the same objectives and constraints to determine the load paths and remove superfluous material. The design which gave the best compromise between mass saving and design risks was then chosen for development.

Manufacturing constraints were added to the topology optimization region containing the load-bearing aluminium structure for the design interpretation phase. Using the raw optimization results, a further collaborative work program between GRMs Finite Element (FE) analysts and Jaguar Land Rovers (JLR) design engineers led from an interpretation of an organic-shape into a manufacturable aluminium sump. A lightweight non-structural plastic reservoir inside the sump ensured the design was oil-tight. The combination of the aluminium skeleton and the oil-retention plastic formed the hybrid material sump.

The Reinforcement Derivation Method (RDM) was used on more mature design iterations to reinforce the new sump by highlighting areas altered during the interpretation phase and guarantee all stiffness requirements were met.

Topology optimization and RDM with stiffness, strength and manufacturing constraints were used to develop a hybrid material sump from a blank page leading to a mass reduction of 20% against the baseline without losing any performance and gaining additional secondary benefits.

274 Modified Equivalent Static Load Methods in Topology Optimization of Flexible Multibody Systems

Ali Moghadasi, Alexander Held, Robert Seifried

Topology optimization has been used in recent years to optimize flexible members in multibody systems undergoing large motion. The optimization process minimizes the objective function while satisfying defined constraints. In contrast to static systems, the objective function and constraints are time dependent in a flexible multibody system. However, a discrete optimization problem can be achieved using the equivalent static load method (ESLM), suggested by Kang et al. (2005). In this way, the optimization process is greatly simplified, yet it is decoupled from the flexible multibody simulation.

In this work, two modified approaches in implementing the ESLM in flexible multibody systems are developed and compared to a fully integrated optimization process where the complete time response of the flexible multibody system is considered in the calculation of loads, objective function, constraints and the gradients.

Initially, for the sake of comparison, the original implementation of the ESLM by Kang is addressed. Thereby, in an outer iteration, the flexible multibody simulation is performed and a set of equivalent static loads are calculated. Then, in an inner iteration, topology optimization is carried out using the equivalent loads from the outer loop. The first modified approach is based on the original implementation of the ESLM by Kang whereby the inner iteration is replaced by a single topology optimization iteration. The second modified approach implements the ESLM in a fully integrated optimization process. In an outer iteration, the objective function, constraints and the gradients are calculated from the complete time response of the flexible multibody system. Afterwards, the ESLM is used to optimize the flexible structure in an inner optimization loop. Using the application example of a flexible slider-crank mechanism, it is shown that through these modified approaches, improvement in the convergence and minimization of objective function can be achieved.

275 Topology optimization of large scale turbine engine bracket assembly with additive manufacturing considerations

Bradley Taylor, Jamal Zeinalov, Il Yong Kim

The objective of this paper is to perform topology optimization of an assembly structure considering additive manufacturing and the associated expanded design spaces. The examined assembly is an existing turbine engine design, comprised of 44 components, which has undergone rigorous real world testing and verification.

Two different topology optimization approaches were considered, using four distinct load cases, considering various mechanical forces and anticipated inertial loads, meant to replicate the most extreme load cases experienced in takeoff, landing, and operation at altitude. The first optimization considers cut-out topology optimization, in which the sheet metal profile of the original bracket assembly design is maintained, while the size and arrangement of cut-outs is optimized. The second optimization features an expanded design space, meant to be representative of the improved design flexibility afforded by recent advances in metal additive manufacturing technology.

When the design space limited to conventional sheet metal arrangements was considered, a total weight savings of approximately 25% was obtained, while maintaining equivalent maximum displacement and compliance values. In comparison, the increased geometric flexibility associated with the additive manufacturing design space allowed for a weight reduction of 66%, while reducing maximum displacement within the assembly by approximately 50% in each load case.

The expanded design space and the associated drastic volume reduction from the initial design vector present several complications. An incremental design space reduction and refinement is presented. All designs are re-interpreted for manufacturing, with manufacturable designs verified through finite element analysis for comparison with original design. A variety of recommended modelling considerations are presented.

276 Stress-based multiscale topology optimization with self-adaptive cluster cells of lattice structure

Jun Yan, Zhenchao Gao, Da Geng, Tao Yu

Based on Extended Multiscale Finite Element Method[1], thermo-elastic lattice structures made up of spcifical microstructures are analyzed on two geometrical scales. Considering the structural strength, stability and so on, independent design variables are introduced. And stress-based optimization with periodic microstructures is studied. To make the distribution of material more reasonable, self-adaptive multiscale optimization based on stress state of microstructures is established. Here, some numerical examples are presented. In these examples, considering the global structural strength and stability constraints, the influences of the size effects of lattice material microstructure on the optimization design are discussed. Then, multiscale optimization with self-adaptive microstructure are studied and compared with the traditional multiscale optimization to prove its superiority. The established optimization model and corresponding design provide new technical means for the design of engineering structure.

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282 Multidimensional Parametrization of Microcells in Two-Scale Optimization with Sparse Grid Interpolation

Daniel Hübner, Dirk Pflüger, Michael Stingl, Julian Valentin

In two-scale optimization one can decouple the microscopic and the macroscopic level [1]. For this we first choose a parametrization for the microstructure. Then we calculate effective material properties for a given discrete set of parameter values by homogenization. In the second phase, during the optimization itself, we apply an interpolation scheme to obtain the properties for intermediate values of the continuous parameter variables. However, usual interpolation methods suffer from the so called "curse of dimension", i. e. they are only applicable for a low-dimensional parameter space.

We present an interpolation scheme using Sparse Grids [2], which can deal with a higher number of parameters permitting a larger freedom of design. The corresponding basis functions are continuously differentiable allowing the use of gradient-based optimization algorithms. Additionally the interpolation might be used spatially adaptive to return better approximations of the material properties. Nonetheless the method might yield physically impossible material properties due to interpolation errors. We overcome this issue by application of a Cholesky factorization to ensure positive definiteness of the interpolated tensors. We provide comparison to a common C1-interpolation in terms of error estimates and computational costs as well as numerical examples in linear elasticity.

[1] BENDSØE, Martin Philip; KIKUCHI, Noboru. Generating optimal topologies in structural design using a homogenization method. Computer methods in applied mechanics and engineering, 1988, 71. Jg., Nr. 2, S. 197-224.

[2] PFLÜGER, Dirk; PEHERSTORFER, Benjamin; BUNGARTZ, Hans-Joachim. Spatially adaptive sparse grids for high-dimensional data-driven problems. Journal of Complexity, 2010, 26. Jg., Nr. 5, S. 508-522.

283 The concept of Free Beam Section Optimization

Elin Andersen, José Pedro Blasques, Alemseged Gebrehiwot Weldeyesus, Mathias Stolpe

The method of Free Beam Section Optimization (FBSO) is aiming to find the theoretically optimal beam for a given beam problem. FBSO can be used in the conceptual design phase for e.g. wind turbine blades and the results can be used as a first design in aero-elastic analysis.
FBSO is as an extension of the previously developed models and methods of Free Material Optimization (FMO). In the latter, the structure is discretized using solid or shell finite elements, and the design variables are the entries of the elastic stiffness tensor. In this work, beams are discretized using Timoshenko beam elements with Lagrangian shape functions,

and the design variables are the entries of the constitutive stiffness and mass matrices of the beam cross section. The constitutive matrices accounts not only for the material properties, as in FMO, but implicitly also for the geometry of the cross-section and the distribution of material across the cross section.

The work presented is twofold; a static, minimum compliance problem and an eigenvalue optimization problem. The material can be non-homogeneous and anisotropic, which means that there are 21 independent design variables for each constitutive stiffness matrices and 9 independent design variables for each constitutive mass matrices. The non-zero entries of these matrices can vary freely at each element in the beam. The constitutive matrices has to be symmetric and positive semi-definite. The measure of material stiffness is the trace of the constitutive stiffness matrices.

FBSO is a positive semi-definite program, solved using a primal-dual interior point method, which generalizes the methods previously developed for FMO at DTU Wind Energy.

This work presents five numerical examples. To the best of our knowledge, there are no other FBSO problems reported in literature with which we can compare our results. The numerical examples are kept relatively simple, to accommodate comparison with analytical solutions where they exist.

285 Homogenization-based topology optimization for high-resolution manufacturable micro-structures

Jeroen Groen, Ole Sigmund

The objective of this work is to present a projection method to obtain high-resolution manufacturable structures from efficient and coarse-scale, homogenization-based topology optimization results [1]. The focus of this work is on compliance minimization of linear-elasticity problems, for which it is known that the optimal solution is in the space of layered materials, the so-called rank-n laminates. Here rank-2 laminates are optimal for plane problems subject to a single load case, and rank-3 laminates are optimal for plane problems subject to multiple load cases.

In a very appealing approach Pantz and Trabelsi introduced a method to project the microstructures from homogenization-based topology optimization to obtain a solid-void design with finite length-scale [2]. The local structure is oriented along the directions of lamination such that a well-connected design is achieved. This approach paves the way for coarse-scale topology optimization where the projection can be performed on a high-resolution mesh in a post-processing step, without a need for cumbersome and expensive multi-scale formulations.

This work shall be seen as a simplification and improvement of the approach introduced by Pantz and Trabelsi [2]. We simplify the projection approach and introduce procedures for controlling the size and shape of the projected design, such that high-resolution (e.g. 1 million elements in 2D), near-optimal and manufacturable lattice designs for single and multiple loadcase problems can be achieved within a few minutes using a single processor Matlab code on a standard PC.

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286 Optimal design of fiber reinforced composite structures that are fabricated via additive manufacturing.

Felipe Fernandez, James Lewicki, Daniel Tortorelli

Structural optimization has been applied to design Fiber Reinforced Composite (FRC) structures to maximize stiffness and failure load, minimize weight, etc. Unfortunately current structural optimization software does not accommodate manufacturing constraints such as those imposed by Additive Manufacturing (AM). Therefore, substantial modifications are imposed upon optimized designs to make them manufacturable and hence nonoptimal.

We propose to optimize the design of FRC structures that are amenable to AM. The process for our study uses Direct Ink Writing (DIW) wherein FRC is extruded through a moving nozzle and quickly cured thereby forming the structure. The fibers orient themselves with the flow direction. And since the stiffness of the FRC is significantly higher in the fiber direction, we have the ability to tailor the structural properties by tailoring the tool-path of the nozzle. However, not all tool-paths are realizable, e.g., the tool-path cannot change its direction abruptly and the paths on each layer must not overlap.

To accommodate these DIW fabrication restrictions, we propose to define the tool-paths of each printed layer by the contours of a level set function. This level set parameterization allows us to impose many of the DIW constraints.

The structure is modeled by a series of tubular channels with circular cross sections such that the tool-paths form their centerlines. The material of these extruded channels is modeled as a transversely isotropic with symmetry axis tangent to the tool-path.

We apply this technique to maximize the stiffness of FRC three-dimensional structures fabricated via AM. We perform sensitivity analysis with respect to the level set parameterization, making it suitable for use with gradient-based optimization algorithms. Optimized designs are validated via fabrication and testing.

289 Novel cellular structural design method for additive manufacturing

Yiqiang Wang, Michael Yu Wang

Cellular structures (CSs) have long been used for a wide range of engineering applications. However, a systematic and powerful design methodology for creating novel high-performance CSs is still in high demand, especially for a general case with arbitrary types of cellular lattices (spatially-varying, scale-dependent and arbitrarily-shaped). To this end, the paper develops an innovative cellular structural topology optimization (CSTO) approach, which both the global structural geometries as well as the downscaling cell configurations and their layout patterns are optimized. To guarantee the connectivity between two neighbouring optimized cells, a configuration interpolation technique is proposed. The main idea is to construct all the in-between cells by interpolating the two end-frame base cells. Because of their configurational similarities, they can be essentially connected without additional treatments or constraints. Moreover, an improved multiscale finite element approach is studied to transfer the cell mechanical behaviour into the global scale equation at a high accuracy. The method will be tested for the compliance minimization and compliant mechanism design problems. Finally, the optimized CSs will be additively manufactured via the MultiJet printer. To meet the processing capabilities, the minimal size of the optimal solutions should be constrained using the e.g. projection method.

291 Two-scale concurrent topology optimization with multiple micro materials based on principal stress direction

Liang Xu, Gengdong Cheng

This presentation studies two-scale concurrent topology optimization with multiple micro heterogeneous materials subject to volume constraints. Unlike the existing work on concurrent two-scale optimization where only one material with optimal microstructure is used or that with multiple micro material where each material is distributed in a number of prescribed geometrical domains, selection of micro heterogeneous materials in this work is based on direction of principal stresses in macro structure. For a structure composed of m micro materials, the macro elements are classified into m categories according to their principal stress direction and each category is assigned with a uniform micro material. The interpolation scheme for macro elements is based on Discrete Material Optimization (DMO), where each element is assigned with m macro design variables. The categorization process of the macro structure is achieved by proper modification of volume constraints, where the macro design variables are multiplied by penalty functions. The penalty functions make it uneconomical for the usage of micro materials, which do not correspond to the principal stress direction of their macro element. The macro structure and micro material are connected through effective property, which is calculated through novel numerical implementation of asymptotic homogenization method (NIAH). Both macro structure and micro materials are optimized concurrently and analytical sensitivities are calculated with adjoint method. One minimum compliance numerical example of an L-bracket subject to volume constraints, where one micro material correspond to macro domain with principal stress angle near 0 or 90 degrees and another correspond to that with principal stress angle near 45 or 135 degrees, is presented to show the potential of the proposed method.

292 A Comprehensive Study of Calibration Metrics for Optimization-Based Model Calibration

Guesuk Lee, Guilian Yi, Byeng D. Youn

Over the past few years, the advance in CAE and the demand for improving the predictive capability of CAE models has drawn great attention on verification and validation (V&V). Ultimately, the goal of V&V is to bring the maturity of the model as close to the reality as possible. In this context, model calibration, which is the process of estimating unknown inputs in a model by improving the agreement of model predictions with experimental observations, is an important element of V&V.

Optimization-based model calibration is a probabilistic approach for estimating unknown inputs by using optimization techniques. Accuracy and efficiency of optimization-based model calibration depend on the selection of a calibration metric which quantitatively measures the difference between two probability distributions of the system responses of interest from computational prediction and experimental observation. However, to date, no general guideline has yet been proposed to select an appropriate calibration metric.

This study compares existing PDF comparison metrics which are developed for different purposes, for example, likelihood function, Euclidean distance, Kullback-Leibler etc. Firstly, various types of metrics are investigated and reviewed. Secondly, important features that make a good calibration metric for model calibration are summarized. Lastly, existing metrics are evaluated based on requirements outlined. Appropriate metrics for optimization-based model calibration are thus elected according to the evaluation results.

The contribution of this comparative study lies in that, we provide a general guideline for calibration metric selection. Besides, the summarized features of a good calibration metric will provide an insightful guidance for developing new metrics for optimization-based model calibration.

294 Level set-based topology optimization for thermoelectric nanostructures considering the temperature discontinuity, based on the Boltzmann transport equation

Kozo Furuta, Ayami Sato, Kazuhiro Izui, Mitsuhiro Matsumoto, Takayuki Yamada, Shinji Nishiwaki

Thermoelectric devices are attractive as energy recovery systems or temperature control systems due to a unique property: direct energy conversion. When a temperature gradient between two different points on a thermoelectric device exists, a voltage between these two points is generated. Conversely, an existing voltage between two different points on a thermoelectric device generates a thermal gradient. This unique property allows the production of thermal or electric energy with no mechanical vibration or noise, but low conversion efficiency inhibits the application of such devices in conventional systems. Most research on improving conversion efficiency has dealt only with macroscale structures, but recent improvements in nanoscale processing technology has led to effective production of various nanoscale structures and devices, including high-performance thermoelectric devices. However, all such novel designs have been based on researchers' intuition and experience, and there are practically no reports on an optimal design method for such problems. One particular difficulty concerning the construction of an optimization method for nanoscale heat conducting structures lies in the temperature discontinuities at the material interfaces. The phonon Boltzmann transport equation can model nanoscale heat conduction and include these discontinuities, but conventional topology optimization methods such as the density method are particularly cumbersome in this regard. On the other hand, our group has proposed level set-based topology optimization methods that can strictly deal with the discontinuities at material interfaces. In this study, we successfully applied a level set-based topology optimization method using the Boltzmann transport equation for the design of nanoscale heat conducting structures.

295 Toward a Comprehensive Understanding of Uncertainty Effects on Model Predictive Capability in Engineering Analysis and Design under Uncertainty

Heonjun Yoon, Joung Taek Yoon, Hyejeong Son, Byeng D. Youn

Virtual testing has been widely recognized as of great importance in designing and evaluating an engineered product. In many engineering problems, the construction of a computational model for virtual testing starts by deriving an ordinary differential equation (ODE) governing the physics of interest. Since there inherently exist uncertainty and complexity in reality, the ODE-based computational models in a deterministic form fail to emulate accurately the behaviors of the engineered product. The uncertainty effects thus have to be taken into account to improve the predictive capability of the ODE-based computational model, indicating the necessity of 'engineering analysis and design under uncertainty'. Despite advances in uncertainty quantification and propagation methods, however, there is still a great need for a systematic framework that elucidates (1) how to consolidate the effects of different kinds of uncertainty in the input quantities on the output responses, (2) how to incorporate uncertainty arising from conscious approximations in modeling, lack of data, and being incognizant of incomplete knowledge. The primary objective of this study is thus to make steps forward to a comprehensive understanding of the uncertainty effects on the predictive capability of the ODE-based computational model in accordance with uncertainty analytics. This uncertainty analytics provides taxonomy to classify and identify the source and type of uncertainty in engineering analysis and design. The source is divided into physical, model form, and statistical uncertainty, while the type includes aleatory and epistemic uncertainty. Depending on the awareness of the existence, epistemic uncertainty is further divided into recognized and unrecognized blind uncertainty. The contribution of this study lies in that we provide an insightful guideline on how to manage uncertainty in the decision-making process for developing the engineered product in a cost-effective manner.

296 Topology optimization in advanced wave problems

Fengwen Wang, Ole Sigmund

Topology optimization has been successfully employed to various wave problems in the past two decades, including acoustic and optical problems. In this study, we aim to explore the application of topology optimization in more advanced wave problems.

Dirac points are points in the band diagram where two or more bands with linear dispersion behavior cross and thereby make up Dirac cones. This phenomenon has been found in classical periodic systems including photonic and phononic crystals [1,2]. Dirac cones have been demonstrated to possess fascinating properties, such as enabling large-area lasers [3] and zero-index behavior [1,2]. Previously Dirac cones have been designed via a tedious trial-and-error approach. More recently, topology optimization has been employed to design Dirac points by excitating crystals using prescribed model profiles [4]. In this work, we present an approach to design Dirac cones using topology optimization in a more systematic way based on band structure calculation of crystals. The design of Dirac cones has been formulated as an optimization problem to tune the dispersions at targeted points in a band structure. Both photonic and phononic crystals are designed to realize single or double Dirac cones using the proposed approach, including both 2D and 3D crystals. Based on the optimized designs, the relation between Dirac cones and zero-index behavior is further investigated.

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297 Model-based control of dynamic frictional contact problems using the example of hot rolling

Stefan Werner, Michael Stingl, Günter Leugering

We use the example of hot rolling to develop a comprehensive optimization approach that is based on a mathematical model of the underlying manufacturing process. More precisely, we study an optimal control problem that is designed to minimize cutting scrap while taking industrial specifications and technical limitations into account.
The deformation of the metal workpiece is described through the basic equations of nonlinear continuum mechanics, which are here coupled with an elasto-viscoplastic material model based on a multiplicative split of the deformation gradient. We assume that the deformations of the rolls can be neglected and thus we add unilateral frictional contact boundary conditions. It is well known that the associated control-to-observation map is non-differentiable due to changes of state resulting from elasto-viscoplastic material behavior and frictional contact. However, we still want to apply gradient-based methods to solve the optimal control problem and therefore have to make sure that derivatives of cost functional and constraints exist. To resolve this issue, we first regularize all non-differentiabilities and subsequently apply the direct differentiation method to obtain sensitivity information.
We moreover formulate a suitable algorithm and discuss numerical results for a real-world example to illustrate its capability.

298 Multiscale approaches in topology optimization

Ole Sigmund, Jeroen Groen, Jun Wu, Simon Dyring, Niels Aage

Fired by recent progresses in additive manufacturing techniques, multiscale topology optimization approaches have recently received intense interest and many efficient and interesting approaches have been presented.

Common challenges of multiscale schemes include lack in separation of scales, tiling of locally optimized microstructures and manufacturability. This paper discusses various new approaches to overcome these challenges performed within the TopOpt group at the Technical University of Denmark.

In one approach we revisit the original homogenization-based topology optimization schemes and suggest a simple graphical projection scheme that realizes fine-grained optimal structures from coarse scale homogenization solutions [1]. The scheme includes length-scale constraints on solid and void features. Further, we demonstrate how the same scheme can be used to provide high quality starting guesses for truss and frame optimization with large numbers of elements.

In another approach we introduce a local volume constraint to provide porous and optimized infill structures for closed-walled 2d and 3d structures realized by additive manufacturing technologies [2]. By adding advanced projection schemes we allow variable outer shape to be included in the design process as well. The structures provide two-scale designs without the requirement of separation of scales.

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299 Self-supporting structure design in additive manufacturing through Moving Morphable Component/Void (MMC/MMV) based explicit topology optimization

Xu Guo, Jianhua Zhou, Weisheng Zhang

One of the challenging issues in additive manufacturing (AM) oriented topology optimization is how to design structures that are self-supportive in a manufacture process without introducing additional supporting materials. In the present contribution, it is intended to resolve this problem under an explicit topology optimization framework where optimal structural topology can be found by optimizing a set of explicit geometry parameters. Two solution approaches established based on the Moving Morphable Components (MMC) and Moving Morphable Voids (MMV) frameworks, respectively, are proposed and some theoretical issues associated with AM oriented topology optimization are also analyzed. Numerical examples show that the proposed approaches do have the capability to find optimized designs where overhang angle constraints can be fully respected. Besides optimal structural topology, the build orientation of AM can also be optimized with use of the proposed approaches in a straightforward way. Compared with existing approaches, the distinctive feature of the proposed approach is that it solves the corresponding problem through a totally explicit treatment. Furthermore, extending the proposed methods to three dimensional (3D) problems can be achieved by introducing 3D printable features in the problem formulation.

300 Explicit three dimensional topology optimization via Moving Morphable Component/Void (MMC/MMV) approach

Weisheng Zhang, Jishun Chen, Xu Guo

Three dimensional (3D) topology optimization problems always involve huge numbers of Degrees of Freedom (DOFs) in finite element analysis (FEA) and design variables in numerical optimization, respectively. This will inevitably lead to large computational efforts in the solution process. In the present paper, an efficient and explicit topology optimization approach which can reduce not only the number of design variables but also the number of degrees of freedom in FEA is proposed based on the Moving Morphable Component/Void (MMC/MMV) solution framework. In the MMC/MMV approach, the topological change of a structure is achieved by the deformation, intersection and merging of a set of closed parametric curves (for 2D problems) or parametric surfaces (for 3D problems) that represent the boundary of the structure. Unlike the traditional level set approach, there is no need to introduce an extra level set function defined in a higher dimensional space to represent the structural boundary implicitly in the MMC/MMV approach. This greatly reduced the number of design variables involved in the optimization problem. In the present explicit boundary evolution-based approach, the computational effort associated with FEA can be reduced substantially by removing the unnecessary DOFs from the FE model at every step of numerical optimization. Numerical examples demonstrate that the proposed approach does can overcome the bottleneck problems associated with a 3D topology optimization problem in a straightforward way and enhance the solution efficiency significantly.

301 A new approach for designing graded lattice/porous structures based on Moving Morphable Component/Void (MMC/MMV) topology optimization framework

Chang Liu, Weisheng Zhang, Xu Guo

With the rapid developments in 3D printing technology, structures with graded lattice/porous microstructures have found increasing usages in many application areas to fabricate lightweight structures, heat exchangers, energy absorption components, aircraft engines, etc. Recent years witnessed a growing interest on developing methods that can be used to generate sparse, strong and stable infill structures that can be manufactured by advanced 3D printing technologies.

In the present work, a new approach for designing graded lattice/porous structures is developed based on Moving Morphable Components/Voids (MMC/MMV) topology optimization framework. The essential idea is using a set of moving morphable components/voids as the basic building blocks of topology optimization. The position and geometry of each component/void are described by a set of explicit parameters and the components/voids are allowed to be overlapped with each other. The topology of the lattice/porous structure can then be optimized by changing the shapes and layout of the components. Variable connection technology is also introduced in the problem formulation to generate graded microstructures. Since in the proposed solution framework, the topology description is totally independent on the resolution of the finite element mesh for structural analysis, the number of design variables can be reduced substantially with use of the proposed approach. Several numerical examples provided demonstrate that the effectiveness of the proposed approach to design graded lattice/porous structures with exceptional properties.

302 Bounded low failure probability estimates with scarce samples using importance sampling

Kiran Pannerselvam, Palaniappan Ramu

Sampling based approaches like Monte Carlo (MC) simulation require a large number of samples for estimating very low failure probabilities (1e-5) accurately. Variance reduction techniques like Importance Sampling, Separable MC, and Markov Chain MC are used to improve the accuracy of such estimations with lesser number of samples. Importance Sampling uses the trick of sampling from another distribution, which is located around the zone of interest of the primary distribution. Thereby reducing the number of samples required for a low probability estimate. In the context of reliability-based structural design, the limit state function is usually separable and is of the form Capacity (C)-Response (R). The importance sampling function is usually located in the region where these distributions overlap each other. However, often, the distribution information of C and R themselves are not known and we have only scarce realizations of them.

In this work, we propose approximating the Probability Distribution Function (PDF) and the Cumulative Density Function (CDF) using kernel functions. It was observed that the probability estimates were affected by the approximation of the CDF and PDF more than the location of the importance sampling function. Hence we assume an importance sampling function which is always normally distributed whose mean is at R=C with a fixed coefficient of variation of 10%. Since the probability estimate depends on the approximation, which in turn depends on the underlying samples, we use bootstrap to quantify the variation associated with the distributions. These bootstrap bounds are then propagated in the importance sampling framework to obtain bounded low failure probability estimates.

The method has been successfully demonstrated on a suit of statistical distributions. The final paper will discuss additional analytical examples in the context of Reliability based design optimization.

303 A PDE-based approach to constrain the minimum overhang angle in topology optimization for additive manufacturing

Emiel van de Ven, Matthijs Langelaar, Can Ayas, Robert Maas, Fred van Keulen

Additive manufacturing has become increasingly popular because it enables the production of complex, topology optimized, parts which cannot be manufactured by conventional production methods. However, additive manufacturing also exhibits some design limitations, one of which is the overhang constraint. Since most additive manufacturing methods build a product layer upon layer, sufficient support between the successive layers is required and thus allowable overhang of the part is limited. Instead of adapting designs after optimization to meet this limitation, and thereby compromising their optimality, a design-for-manufacturing approach is preferred. Therefore, imposing an overhang constraint in topology optimization is a highly demanded feature from industry.

Several formulations to impose overhang limitations have been proposed recently, but these typically are highly nonlinear and mesh-dependent. In this work we present a PDE-based overhang constraint, where overhang is detected using front propagation. This overhang detection can be seen as a very crude process simulation, where with every added layer, the front evolves with the product. By delaying the front when it propagates in directions below the minimum allowable overhang angle, overhang can be detected by studying the arrival time field of the front.

Due to the continuous nature of the constraint, it can be used on non-regular mesh types, and for any value overhang angle. Furthermore, front propagation problems are well studied. By using existing numerical techniques such as the fast marching method to solve the front propagation problem, the overhang constraint and its design sensitivity can be evaluated with little computational cost.

Numerical examples on unstructured tetrahedral meshes will be presented for several compliance optimizations with overhang constraint.

304 Parameterization setup for metamodel based optimizations of Tailor Rolled Blanks

Niklas Klinke, Axel Schumacher

Tailor Rolled Blanks (TRB) are an established lightweight application for highly stressed structural parts in automotive industry. By varying the rolling gap, parts with load adapted thickness profiles and continuous transitions are manufactured. The rolling process itself is subjected to several manufacturing constraints which have to be considered in the numerical optimization. It has been shown that the thickness run parametrization has significant impact on the optimization result and the associated computational cost.

The goal of the presented methods is to systematically assess the number of areas of constant thickness (plateaus) and setup a thickness run parametrization for subsequent metamodel based TRB optimization.

Starting from a baseline design, the rolling direction is determined based on an optimality criterion. Three approaches are then compared to create an initial thickness distribution along the axis of maximum inhomogeneity without the need of additional non-linear function evaluations:

1. Single iteration ESL-optimization
2. Single iteration HCA scheme
3. Scaling of stress distribution

The created distributions have to be interpreted in order to generate a parametrization for metamodel based optimization which takes all TRB design constraints into account. The interpretation is performed by solving an optimization tasks, resulting in the thickness run with the least deviation to the input thickness distribution.

Two application examples are presented. A crash beam subjected to three point bending is optimized using two load case setups. Also a submodel of the NCAC Toyota Yaris in full frontal crash is used to optimize the front rail assembly. The results of the subsequent metamodel based optimization are compared to the results of metamodel based optimizations with a general parametrization setup.

305 A study of the application of element free methods in topology optimization

Bence Balogh, János Lógó

The goal of the study is to compare the application of element free methods versus conventional ones in topology optimization. The topology optimization design of 2D continuum structures is formulated based on the global weak form of the problem, using the element free Galerkin (EFG) method. The moving least squares (MLS) method is used to construct shape functions with compactly supported weight functions, to achieve meshless approximations of the field variables. The direct method is included to enforce the essential boundary conditions because of the lack of the Kronecker delta function property of MLS meshless shape functions. Methods are compared in terms of computational time, numerical issues, advantages and shortcomings, and overall applicability in general. Considering the relative density of nodes as design variable, and the minimization of the compliance of the structure as an objective function, the mathematical formulation of the topology optimization model is developed with a variational framework. The topology optimization problem is solved by the optimality criteria method and seq. quad. programming. Finally, the feasibility and efficiency of the proposed methods are illustrated both for deterministic and reliability-based cases, with several 2D benchmark examples that are widely used in the topology optimization literature. In the reliability-based case, reliability constraints are introduced to the deterministic problem. The optimal topology is searched with respect to uncertain loading using a game theoretic framework. Finally, it is shown through examples, that the mesh distortion that exists in the finite element-based design approach is effectively resolved for large shape changing design problems. The number of design iterations is reduced because of the accurate sensitivity information. We also find that the reliability based model yields structures that are more reliable than those produced by deterministic topology optimization.

306 Accelerating sampling based methods for reliability analysis through on the fly reduced order modeling

Christian Gogu, Anirban Chaudhuri, Christian Bes

Being able to efficiently run reliability analyses on large scale finite element problems is becoming a growing concern in academia and industry. This challenge can be addressed in two ways, by developing efficient methodologies for reliability analysis and by developing efficient ways to solve large scale finite element problems.
Monte Carlo simulation is among the most popular methods for reliability analysis. Unfortunately it quickly becomes intractable on large scale finite element problems. More advanced sampling based reliability estimation methods have thus been developed, such as importance sampling, separable Monte Carlo simulation, Markov chain Monte Carlo. Surrogate based approaches, notably kriging based adaptive approaches, have also been developed and shown to be efficient at solving reliability problems. Advanced sampling based approaches and sur-

rogate based approaches can lead to reductions of several orders of magnitude in the cost of reliability analysis compared to crude Monte Carlo.
Another path than can be followed is developing efficient ways of solving the numerical model. In case of finite element modelling, reduced order models (ROM) have been proposed to approximate the exact solution. Reduced order models by projection, also known as reduced basis models, are a particular kind of ROM that involve solving the finite element problem projected on a usually very low-dimensional basis.
The aim of the present paper is to illustrate how a combination of advanced sampling based techniques and reduced basis modelling can lead to further significant computational cost savings. An adaptive on the fly construction of the reduced basis is proposed in this context. The method is illustrated and compared on several sampling based approaches on a thermal reliability design problem of a rocket engine combustion chamber. We find that the combination of these two approaches can lead to an additional increase in efficiency by up to a factor of six.

308 Gaussian Process for Aerodynamic Pressures Prediction in Fast Fluid Structure Interaction Simulations

Ankit Chiplunkar, Elisa Bosco, Joseph Morlier

The interaction between inertial, elastic and aerodynamic forces for structures subjected to a fluid flow may cause unstable coupled vibrations that can endanger the structure itself. Predicting these interactions is a time consuming but crucial task in an aircraft design process. In order to reduce the computational time surrogate reduced order models can be used in both structural and aerodynamic models. More over it is possible to avoid launching CFD computations at every time step. A database of aerodynamic pressure distribution on the structural component can be created conveniently sampling the space of the structural model DoF. Starting from the knowledge of the pre-computed data-set a Gaussian Process can be applied to predict the pressure distribution on an unexplored point of the space of DoF. The knowledge of the standard deviation can be used to give indications on where to launch further CFD computations to enrich the database. This technique will be first applied to a database of pressures obtained using the software Xfoil, later it will be applied to CFD simulations of type RANS launched with elsA on one Flap track Fairing of an Airbus aircraft.

309 Enhanced coupling in magnetoelectric composites by material design

Jayachandran K P, José Guedes, Helder Rodrigues

Electrical control of magnetization offers an extra degree of freedom in materials possessing both electric and magnetic dipole moments. Magnetoelectric (ME) multiferroics are a new class of such materials possessing simultaneously ferroelectric and ferromagnetic properties in the same phase exhibiting linear coupling and have recently drawn increasing interest due to their potential applications in multifunctional devices [1, 2]. The coupling between ferroelectric and ferromagnetic order parameter is mediated by an elastic strain between the two phases. Natural multiferroic single-phase compounds are rare and their ME coupling responses are either weak or occurs at temperatures too low (since most mutliferroics exhibit low Curie temperatures) for practical applications. An alternative approach to obtain a ME effect is through multilayered composites of a ferroelectric and a ferromagnetic material [1]. An applied electric field creates a piezoelectric strain in the ferroelectric, which produces a corresponding strain in the ferromagnetic material and a subsequent change in magnetization. Various efforts to improve the value of ME coupling coefficient have been made by modifying preparation techniques of the samples, by the proper choice of materials or different structures and by choosing different thickness of the samples [1]. In this study, we have applied a stochastic optimization for arriving at the solution for maximum "ME coupling coefficient α" of a laminar ME composite with the thickness and orientation of phases as design variables. As α could not be expressed explicitly as function of design variables, we have used the simulated annealing combined with a generalized Monte Carlo scheme for optimization problem. Optimal microstructure with single and poly-crystalline configurations that enhances the overall α is identified.

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310 Generating the Best Stacking Sequence Table for the Design of Blended Composite Structures

F. Farzan Nasab, H. J. M. Geijselaers, I. Baran, A. de Boer

In order to improve the ability of a large scale composite structure to carry tensile or compressive loads, stiffeners are added to the structure. The stiffeners divide the structure into several smaller panels. For a composite structure to be manufacturable, it is necessary that plies are continuous in multiple adjacent panels. To be able to prescribe a manufacturable design, an optimization algorithm can be coupled with a reference table for the stacking sequences (SST). As long as the ply stacks are selected from the SST, it is guaranteed that the design is manufacturable and all strength related guidelines associated with the design of composite structures are satisfied. An SST is made only based on strength related guidelines. Therefore, there exist a large number of possibilities for SSTs. Minimized mass is a typical goal in the design of aircraft structures. Different SSTs result in different values for the minimized mass. Thus it is crucial to perform optimization based on the SST which results in the lowest mass. This paper aims to introduce an approach to generate a unique SST resulting in the lowest mass. The proposed method is applied to the optimization problem of a stiffened composite structure resembling the skin of an aircraft wing box.

312 Bootstrap guided information criterion for reliability analysis using small sample size information

Eshan Amalnerkar, Jihoon Kim, Woochul Lim, Tae Hee Lee

Several methods for reliability analysis have been established and applied to engineering fields bearing in mind uncertainties as a major contributing factor. Small sample size based reliability analysis can be very beneficial when rising uncertainty from statistics of interest such as mean and standard deviation are considered. Model selection and evaluation methods like Akaike information criteria (AIC) have demonstrated efficient output for reliability analysis. However, information criterion based on maximum likelihood can provide better model

selection and evaluation in small sample size scenario by considering the well-known measure of bootstrapping for curtailing uncertainty with resampling. Our purpose is to utilize the capabilities of bootstrap resampling in information criterion based reliability analysis to check for uncertainty arising from statistics of interest for small sample size problems. In this study, therefore, an unique and efficient simulation scheme is proposed which considers the best model selection frequency devised from information criterion to be combined with reliability analysis. It is also beneficial to compute the spread of reliability values as against solitary fixed values with desirable statistics of interest under replication based approach. The proposed simulation scheme is verified using a number of small and moderate sample size focused mathematical examples with AIC based reliability analysis for comparison and Monte Carlo simulation for accuracy. The results show that the proposed simulation scheme favors the statistics of interest by reducing the spread and hence the uncertainty in small sample size based reliability analysis when compared with conventional methods whereas moderate sample size based reliability analysis did not show any considerable favor. The reliability of a piezoelectric device is evaluated using proper choice of limit state function under the proposed scheme of reliability analysis.

313 Mixed variable approach for topology optimization of roof trusses

Kristo Mela, Markku Heinisuo

In this study, the applicability of the classical pin-jointed truss model is assessed for optimization of roof trusses according to the European design standard EN 1993 for steel structures. The trusses considered consist of steel members with rectangular hollow section profiles taken from a discrete catalogue of the producer. Topology optimization based on the ground structure approach is carried out for typical truss spans and heights found in industrial buildings. Member strength and buckling constraints are included in the problem, and additional constraints for joint layout and geometry as well as for manufacturability are incorporated. The problem formulation is based on a mixed variable approach, where binary variables are employed for determining the topology and member profiles, and member forces and nodal displacements are taken as the continuous state variables. This formulation enables finding the global optimum by deterministic methods. Moreover, member buckling can be treated appropriately in topology optimization, and topological constraints can be easily incorporated as linear constraints in the binary variables.

As the pin-jointed structural model does not take bending of the chords and eccentricities of the joints into account, and the resistance of joints is excluded from topology optimization, the optimum truss does not necessarily comply with the rules of the design code. Consequently, the trusses obtained from topology optimization are analyzed by an appropriate structural model and the resistance of members and joints according to the rules of EN 1993 is verified.

The results of the assessment indicate that the pin-jointed model is in general suitable for member design, but the resistance of the more heavily loaded joints is often exceeded. While not rendering the pin-jointed model entirely inapplicable, these details require further attention for the results of optimization to be directly usable by the structural designer.

315 An optimization strategy for variable-thickness sandwich composite structures

François-Xavier Irisarri, Cédric Julien, Dimitri Bettebghor, Florian Lavelle, Kevin Mathis

The present work deals with the parametric optimization of variable-thickness sandwich composite structures for spatial applications. A three-step optimization strategy is presented. The first step combines linear finite element analysis of the structure and gradient-based optimization to find an idealized design. The optimizer returns the best core material and skin thickness distributions and the homogenized stiffness distribution of the composite shells of the structure. The membrane and bending stiffness matrices of the sandwich panels are parameterized using the lamination parameters of the skin laminates and the thicknesses of both the core material and the skin. Additionally, the transverse shear stiffness matrix of the sandwich material is evaluated as a function of the design variables, using a dedicated response surface. In a second optimization step, an evolutionary optimizer is used to retrieve the skin laminates that best match the optimal stiffness and thicknesses distributions. Variable-thickness sandwich panels are represented through stacking sequence tables. No structural analysis is performed at step two, thus a third optimization step is required to ensure the feasibility of the discrete design with respect to mechanical requirements. The stacking sequence tables found are used to define the stiffness of the sandwich panels as a function of the skin thickness within a continuous optimization using the local skin stiffness as design variables. The overall strategy is applied to the test case of Ariane 5 Sylda secondary payload adapter, considering global stiffness, strength and global buckling requirements.

316 Experimental and Numerical Analysis of Mechanical Properties of Tape Spring Hinges and Optimal Design

Hongling Ye, Yang Zhang, Qingsheng Yang, Ramana V Grandhi

A tape spring with outstanding self-driven, self-locking performances is studied under pure bending load. A novel hinge using three tape springs is investigated, and this paper presents a complete set of optimization process for the hinge. Firstly, the steady moment and maximum stress of the hinge in deploying and folding process are studied using numeral simulation, and verified by experiments using particularly designed apparatus. Secondly, the analysis of effect from geometric parameters on performances of the hinge is carried out, which shows that both thickness and subtended angle have significant influences on steady moment. And then, optimal of the hinge that aims to maximize steady moment subjected to allowable stress is estalished based on the Response Surface Methodology (RSM) and the analysis of parameters' effects. Lastly, Large Scale Generalized Reduced Gradient algorith (LSGRG) is selected to solve optimal equations. The optimal results show that steady moment is increased by 19,5% and maximum stress is within the safety limits. The proposed method is of great significance for designing novel deployable structure with higher stability and reliability.

317 Improved adaptive-loop method for non-probabilistic reliability-based design optimization

Yutian Wang, Peng Hao, Chen Liu, Fangzhou Wu, Bo Wang

Taking the unique superiority to handle the uncertain-but-bound problem, convex model is widely used in non-probabilistic reliability-based design optimization (NRBDO). Typically, parallel-loop method, serial-loop method and single-loop method are three basic approaches for non-deterministic design optimization. It is an essential issue to combine them together and exploit their own advantages to the full. In this paper, an improved adaptive-loop method (IALM) for NRBDO is proposed to improve the optimization efficiency. In the first phase, the reconstruct constraint function is formulated to enhance the reliability analysis with single-loop method. Due to the efficiency of single-loop method and robustness of parallel-loop method, the IALM can adaptively select a proper one based on the proposed judgment criteria. To further improve the robustness and efficiency of parallel-loop method, the enhanced chaos control (ECC) method is introduced in this paper. Numerical examples are utilized to demonstrate the effectiveness of the proposed method by comparison with other existing methods in terms of numerical efficiency and stability.

318 Multimodal Optimization of Auxiliary Objectives in Structural-Acoustic Problems to generate Local Coarse Models for Multifidelity Optimization.

Gesche Fender, Koushyar Komeilizadeh, Steffen Marburg, Fabian Duddeck

For reduction of interior noise in car body design often optimization of auxiliary goals is used, one example being the optimization of the equivalent radiated power (ERP), which can be computed solely considering the vibrating structure. Since auxiliary goals do not capture all characteristics of the actual objectives behaviour, it is beneficial to perform multimodal optimization at that level. Hence, not only the global optimum of the auxiliary objective is found, but multiple local and global optima can be identified in one optimization run. For this a multimodal variant of the differential evolution (DE) algorithm is used. As shown in previous work, those multiple optima can be used as candidate solutions. The simplest way of doing this is by using them as inputs for the actual objective (the fine model), and then choosing the solution that performs best there, instead of the one that performed best on the auxiliary objective. In the aforementioned case of ERP as auxiliary goal, the actual objective is usually the sound pressure at certain locations inside the drivers cabin, and the fine model a coupled structural-acoustic simulation. Here, in a further step, the knowledge gained from the multimodal coarse model optimization is integrated into optimization of the fine model in a multifidelity optimization. Therefore fast, local coarse models are built based on the candidate solutions, which can then be used as surrogates in a multifidelity optimization of the sound pressure inside the cabin.

As optimization problem, positioning of damping layers on the vibrating panels of a harmonically excited cabin to reduce interior noise is shown, although the method can be applied to other structural optimization problems if the considered objective shows multimodal behavior and a suitable coarse model is available.

320 Fatigue resistant designs using stress-based topology optimization

Maxime Collet, Simon Bauduin, Eduardo Fernández Sanchez, Pierre Duysinx

Stress based topology optimization has received great interest since almost 20 years because of the innovative designs that can be achieved to answer strength requirements. Fatigue is an important mode of failure in mechanical engineering and accounting for it as soon as the early stage of design using topology optimization sounds primordial. Literature reports many good results for shape optimization whereas in the field of topology optimization several authors have shown that considering fatigue in an optimization framework leads to more relevant solutions where fluctuating loads are involved.
In order to check the good behavior of the implementation, we first investigate the implementation of an advanced fatigue criterion, i.e. the multiaxial Dang Van criterion , in the framework of a density-based topology optimization problem. The choice of this fatigue criterion is justifed by its good applicability in automotive or aeronautic industry as well as its relevancy with respect to experimental results. We present the sensitivity analysis with stress constraints and present some classical benchmarks to illustrate the behavior of the optimized solution.
In a second time, we introduce the fatigue resistance in the well-known microstructural design. The new additive manufacturing techniques allow to fabricate components exhibiting architectured materials. In this perspective, ensuring the fatigue resistance of the cellular material will by extension ensure the structural integrity of the overall structure itself.
Both types of optimization framework are evaluated in term of their numerical performances and are compared to classical results generated by a regular stress-based topology optimization. Finally, the results are 3D-printed to assess for their manufacturability.

321 High-Fidelity Aero-Structure Gradient Computation Technique with application to the CRM Wing Design.

Timothée Achard, Christophe Blondeau, Roger Ohayon

To improve the design of flexible wings, gradient-based multidisciplinary design optimization techniques are effectively and widely used. However, gradients calculation is not trivial and can be costly when high-fidelity models are considered. At Onera, the objective of a previous work from the authors was to develop an aero-structure gradient capability from scratch, by systematic differentiation of discretized aero-elastic equations in the elsA aeroelasticity module. Only aeroelastic gradients computation capability, i.e. gradients of aeroelastic functions with respect to aerodynamic shape parameters, was available so far. This module has been recently extended in order to deal with structural design parameters in direct and adjoint mode.

The efficiency of the adjoint approach holds when a reduced number of responses is considered compared to a large set of design parameters. However, an industrial wing box sizing for preliminary design considers up to several hundreds of design parameters and up to several tens of thousands of structural constraints. Considering these difficulties, the authors have proposed in a previous paper a new strategy to compute high-fidelity aero-structure gradients. This strategy is based on an uncoupled non-intrusive approach benefiting from the linearized aerodynamic theory. The main advantage of the method is the independency of the computational cost with respect to the number of constraints and potentially with respect to the number of structural design parameters.

The aim of this paper is to demonstrate this new coupled gradient capability through an inverse design problem. More specifically, the objective is to match a target twist distribution on the Common Research Model wing. The two approaches will be investigated on this particular problem and the selection will consider criteria such as accuracy, efficiency, and applicability on practical industrial problem.

322 A topology optimization method for molecular gas dynamics based on the Boltzmann equation

Ayami Sato, So Okamoto, Takayuki Yamada, Kazuhiro Izui, Shinji Nishiwaki, Shigeru Takata

The behavior of gas flows at low pressures or in microscale systems even at normal pressures is not correctly described in the range of continuous fluid dynamics, that is, as a Navier-Stokes system, because collisions among the gas molecules are relatively scarce. The behavior of such rarefied gas flows are usually described by the Boltzmann equation, based on molecular gas dynamics. Flows of rarefied gas can be induced along a temperature gradient without applying any external force, and there are studies about devices exploiting this property, such as the Knudsen compressor. Practical applications of a Knudsen compressor would be especially suitable in MEMS, due to their advantage of having no moving parts, but the designs of devices based on the properties of rarefied gas flows have been limited to relatively simple shapes so far, and the structures do not always maximize performance. The use of a topology optimization method for the design of such devices should improve the performance dramatically, being based on mathematical and physical principles. In conventional topology optimization methods for fluid problems, the Navier-Stokes equation is extended to the entire design domain that includes fluid and solid domains, by considering the solid domains as porous media and imposing fictitious external forces on the solid domains. On the other hand, since we analyze rarefied gas flows using the Bhatnagar–Gross–Krook (BGK) model of the Boltzmann equation in this study, this approach cannot be used. We therefore propose a new method for extending the BGK model equation to the solid domains and incorporate this in the proposed topology optimization method. Furthermore, we confirm the validity of the proposed method through several numerical examples.

323 Stress analysis and lay-out optimization of composite materials with periodic microstructures

Pedro Coelho, José Guedes, Hélder Rodrigues, João Cardoso

Material design is an active research field since composites have met increasingly interest, for instance, in lightweight construction as it happens in aerospace industry. One assumes in the present work a given macroscopic stress field (one that may occur at a certain point of a macro-structure) and computes through homogenization the micro-stress distribution across the two (weaker and stronger) composite constituents mixed in a unit-cell domain Y, i.e., the representative volume element (RVE) of the material heterogeneous medium.

Stress gradients depend a lot of design details but typically the stress function is highly non-linear. In the frame of finite element models for material microstructures one pursues here an investigation about mesh convergence. By means of ever-increasing mesh refinements and shape functions order one evaluates convergence of micro-stress measures and concludes about mesh quality. Besides investigating the quality of numerical approximation to the stress function, one also may address the quality of the homogenization stress predictions comparing them to the actual composite by repeating an unit-cell a limited number of times and subjecting the resulting numerical model to a battery of load tests for stress assessment. Since stress distribution is strongly design dependent, that motivates one to pursue optimal design of the material microstructure to comply with admissible stress criteria. The inverse homogenization method using density-based topology optimization is applied here for such purpose. This is quite a challenge not only because of the aforementioned non-linearity of the stress function but also due to the singularity phenomena which one overcomes using relaxation techniques. Some preliminary results are obtained in order to get some insight into the fine structure of composite materials and the influence of the stresses therein.

324 New optimization sequence for the Graph and Heuristic based Topology Optimization of crashworthiness profile structures

Christopher Ortmann, Axel Schumacher

For structures subjected to linear static loads there exist a number of efficient topology optimization methods. However, these methods cannot be used for crashworthiness structures due to the occurring nonlinearities and the dynamics. These nonlinearities have different kinds of sources: geometry (e.g. large displacements and rotations), boundary condition (e.g. contact) and material (e.g. plasticity, failure and strain rate dependency). Furthermore the huge number of design variables, the existence of bifurcation points and the costly determination of sensitivity information cause problems.

The Graph and Heuristic Based Topology Optimization (GHT) [1] addresses these difficulties and can be used for the topology optimization of profile cross sections of crashworthiness structures. In the GHT the actual optimization problem is divided into two optimization loops convoluted in each other. In the outer optimization loop heuristics derived from expert knowledge change the topology of the structure to be optimized, based on simulation data from crash simulations. In the inner optimization loop conventional universal optimization algorithms for the shape and sizing optimization of the structure are used. The geometry of the structure to be optimized is described by a mathematical graph. The graph is generated according to a specially for this purpose developed syntax and also allows complex geometric modifications such as topology changes by the flexible description of the geometry. Graph based algorithms are used for the check of manufacturing constraints.

This contribution presents a new optimization sequence for the Graph and Heuristic Based Topology Optimization (GHT). This sequence reduces the number of necessary function calls and improves the ability of the method to overcome local optima.

[1] Ortmann C, Schumacher A (2013) Graph and heuristic based topology optimization of crash loaded structures. Struct Multidisc Optim 47(6): 839-854

325 Study of different control parameters in a SIMP based topology optimization method for adaptation of structures.

Saad Hafsa, Axel Schumacher

A topology optimization method for the adaption of existing structures to new requirements has been developed and first presented in [1]. The motivation to reuse a structure in a new design is encountered in different disciplines like in civil engineering, biology and the automotive industry. In this last field, two applications have been identified: first, for the design of some motorsports vehicles, a series vehicle is used as a basis and adapted to the specific needs of racing operations. Second, in the context of the electrification of the vehicles, the manufacturers often transform an existing model with internal combustion engine into a battery electric vehicle, which leads to a new mass repartition that has to be compensated. The reinforcement using a beam structure is advantageous because of the low manufacturing and mounting costs and the stiffness to mass ration.
The first presented method allows to find the topology of the reinforcing structure using an optimization method. It has been shown that the performance of the resulting structure is close to the results obtained with the standard method despite the additional constraint. Also, the standard method delivers some reinforcements that do little participate to the improvement of the structure.
Therefor the aim of the actual work is to analyze the mechanical meaning of the results obtained with booth methods. Furthermore, the implemented modification were the penalization of the sensitivities and the filtering method. In this work, alternative implementation regarding how and which elements are penalized and filtered is investigated.

[1] S. Hafsa, A. Schumacher (2016), Topology Optimization Method for the adaptation of existing structures to new requirements, thru addition of framework structures, Proceedings of the 12th World Congress on Computational Mechanics (WCCM XII), Seoul, 24-29 July 2016.

326 Topology optimization with local worst-case damage

Jannis Greifenstein, Michael Stingl

We consider a topology optimization problem in linear elasticity that addresses defects in the local material properties. The studied model may be used for robustness with respect to minor manufacturing errors as well as for locally almost completely failed material. The local material degradation effects are treated as a worst case scenario leading to a bilevel optimization problem. Effectively, a concurrent minimization of the compliance with respect to the topology variable and a maximization with respect to the material defects is done. Representing the degraded material using an inverse interpolation between the non-degraded and degraded Youngs moduli as in [1], it can be shown that the inner maximization problem is concave. This approach was also used for robust truss topology design in [2]. Further reformulation of the lower-level problem yields a strictly concave maximization problem with sparse Hessian and a volume constraint, allowing for a highly efficient solution with second-order methods. Moreover, by using the optimality conditions of this inner problem as a constraint to the outer topology optimization, standard adjoint calculus and gradient based algorithms can be applied for the outer robust topology optimization problem. The optimization problem is derived and motivated. Subsequently, numerical applications are shown for robust topologies with respect to manufacturing errors in additive manufacturing and for local material breakdown.

[1] Achtziger, W., Bendse, M. P., & Taylor, J. E. (1998). Bounds on the effect of progressive structural degradation. Journal of the Mechanics and Physics of Solids, 46(6), 1055-1087.

[2] Achtziger, W., & Bendse, M. P. (1999). Optimal topology design of discrete structures resisting degradation effects. Structural optimization, 17(1), 74-78.

328 Automatic generation, validation and correlation of the submodels for the use in the optimization of crashworthy structures

Carlos J. Falconi D., Alexander F. Walser, Harman Singh, Axel Schumacher

Optimization of large crashworthy systems like a vehicle body in a crash loaded case is a time consuming and costly process. The computation time can be reduced by dividing the large system (main model) into small systems called submodels. These submodels can be effectively used in the optimization to shorten the response times. But the generation of submodels by hand is challenging and requires a lot of effort to validate them. This paper presents a workflow to automatically generate and validate the submodels using various mathematical functions.
A submodel is a region of interest cut out from the large system which is to be analyzed in detail [1]. This detailed analysis can be useful to enhance the local and the global performance of the large crash systems. There are two important parameters to generate a submodel using the so called connecting island algorithm, the threshold ratio and the connecting island value. These parameters are based on an evaluation function which is a structural response with time averaging and space averaging. The size of the submodel depends on these two parameters. The validation of the submodel is a three step process, a local, a global and a response validation. These three processes measure the deviation between the submodel and their counterparts in the large system. The validation process delivers outputs in form of a values which are used as constraints. It is discussed how the validation criteria effects the submodels and their size. The goal is to reduce the size of the large system whereas the deviation in the submodel should be as minimum as possible. To verify this, a correlation between the threshold ratio, the connecting island values, the submodel size and the savings in the computation time is studied and discussed in detail.

[1] Link, S; Singh, H.; Schumacher, A. (2016): Influence of submodel size and evaluated functions on the optimization process of crashworthiness structures", LSDYNA Forum (2016)

329 Multi-fidelity Approaches for Crashworthiness Optimisations

Fabian Duddeck

Normally, the design of structures with respect to crashworthiness is realised via nonlinear and dynamic finite element simulations using an explicit time step scheme. Because of the corresponding high computational effort, special methodologies are required for optimisation and

robustness assessments. For this, different approaches have been established based on simplified or reduced order modelling or on surrogate and meta-modelling. For example, lumped mass approaches, simple beam models or response surface models, like polynomial regression, kriging, and radial basis functions, have contributed to efficient optimization strategies. Here, the appropriate compromise between accuracy and efficiency of the modelling approach has to be identified depending on the applications in different development phases. In early design stages, set-based development is realised increasingly assuring the validity of structural concepts under consideration of lack-of-knowledge robustness. Latter development phases require more precise predictions using highly detailed models. The computational effort is high either due to a large number of different concepts (early phase) or due to models with high complexity (final phase).
Because recent studies of the authors research group have confirmed that single fidelity modelling for crash optimisation cannot be recommended, new approaches for multi-fidelity optimisation (including robustness) will be presented in this paper. Hereby, the focus is laid on problems from the early design phase, but as an outlook aspects for later phases are included. Examples will be shown for frontend optimisation with respect to pedestrian safety, frontal impacts (full and partial overlap and small overlap), and for other crash cases. Based on these applications, methodological aspects of multi-fidelity optimisation are discussed showing the different possibilities of combining low- and high-fidelity crash models in an overall optimisation scheme.

330 Bayesian optimization with variables selection

Malek Ben Salem, Olivier Roustant, Fabrice Gamboa, Lionel Tomaso

Bayesian optimization techniques have been successfully applied in various fields of engineering. Generally, they are used in the case of a moderate number of variables. Therefore, there is a great interest in Bayesian optimization algorithms suitable for high-dimensional problems. Here, we consider the high-dimensional case with a moderate number of influential variables. The basic idea consists in filtering the minor variables in order to enhance the optimization. To do so, new criteria are introduced within the Gaussian Process regression model and a specific set of stationary kernels.

The proposed algorithm combines optimization and variables selection. The points are generated in order to accelerate the optimization and refine the variables selection. The parameters splitting is challenged sequentially thanks to a new criterion called doubt. The algorithm is tested and compared to other methods such as the classical EGO. The results show the efficiency of the algorithm for high dimensional problems when the intrinsic dimensionality is moderate.

331 Automatic selection for general surrogate models

Malek Ben Salem, Lionel Tomaso

In design engineering problems, the use of surrogate models (also called meta-models) instead of expensive simulations have become very popular. Surrogate models include individual models (regression, kriging, neural network...) or a combination of individual models often called aggregation or ensemble. Since different surrogate types with various tunings are available, users often struggle to choose the most suitable one for a given problem. Thus, there is a great interest in automatic selection algorithms.

The main objective of this work is to propose new relevant surrogate model selection algorithms. To achieve such goal, we introduce a criterion to assess the quality of a surrogate model, called Penalized Predictive Score (PPS). It is composed of three complementary components: internal accuracy (on design points), predictive performance (cross-validation) and a roughness penalty.

PPS is universal, i.e. defined for any surrogate model. This lead to two selection algorithms based on PPS.

The two new algorithms generate ensembles of surrogate models. Their weights minimize the PPS of the aggregation. The first algorithm deals with a small number of surrogate models. The second one explores the possible model combinations with a genetic algorithm.

The performances of these algorithms are investigated on 15 classical test functions and compared to different individual surrogate models. The results show the efficiency of our approach. In particular, we observe that the three components of the proposed criterion act all together to improve accuracy and limit over-fitting.

332 Universal prediction distribution for surrogate models

Malek Ben Salem, Olivier Roustant, Fabrice Gamboa, Lionel Tomaso

The use of surrogate models is very convenient in engineering. Their main purpose is to replace an expensive-to-evaluate function by a simple response surface also called surrogate model. Using a set of design of experiments, a surrogate model is built to mimic the behavior of the expensive function.

Some surrogate models are probabilistic. They are generally based on Gaussian assumptions. The main advantage of probabilistic approaches is that it provides a measure of uncertainty associated with the surrogate model in the whole space. This uncertainty is an efficient tool to construct strategies for various problems such as prediction quality enhancement, optimization or inversion.

Away from the Gaussian case, many surrogate models are also available and useful. Nevertheless, they are not all naturally embeddable in some stochastic frame. Hence, they do not provide naturally any prediction error distribution. To overcome this drawback, several empirical design techniques have been discussed in the literature. These techniques are generally based on resampling methods such as bootstrap, jackknife, or cross-validation. However, most of these resampling method-based design techniques lead to clustered sets of points.

We propose a universal method to define a measure of uncertainty suitable for any surrogate model: deterministic, probabilistic and ensembles. It relies on Cross-Validation sub-models predictions. This empirical distribution may be computed in much more general frames than the Gaussian one. For this reason, we call it Universal Prediction distribution.

It allows the definition of many sampling criteria. We give and study adaptive sampling techniques for global refinement and an extension of the so-called Efficient Global Optimization algorithm applicable for all types of surrogate models. The performances of these new algorithms are studied both on toys models and on an engineering design problem.

333 Multidisciplinary structural optimization using of NSGA-II and ε-Constraint method in lightweight application

Vahid Ghaffari Mejlej, Paul Falkenberg, Eiko Türck, Thomas Vietor

In recent years, the automobile industry to produce lighter vehicles with higher levels of safety and competitive price was under more pressure. Light weight structure is engaged with different types of external loads such as static, cyclic, impact, and aerodynamics forces. This multi-disciplines are influenced by a wide range of discrete parameters, such as the number of layers of a composite part, material properties and joining technology beside the continuous parameters such as the size of cross-sections and thickness.
Minimization of weight and cost and maximization of strength and durability of a multi-material structure made of metal and composite goes toward a multi-objective and multi-discipline problem. NSGA-II is implemented as a powerful algorithm in multi-objective problems for finding the best combination of discrete and continuous variables in structural optimization. Since no estimation about the minimum and maximum values of objectives is not present, the use of weighted sum method may incline to results away from the global optimum. While Epsilon method which provides much better organization on the objectives and constraints, seems a better method to select suitable members during the optimization process.
To cut a long time of cyclic simulation for calculating the fatigue life of structure, Epsilon method in two stages is implemented in this study. In the first stage, weight, strength, cost and maximum of Mises and Tsai-Wu stress were assessed and evaluation of second stage is carried out only on structures which have satisfied the provisions of the first stage. The combination of Epsilon method and NSGA-II to solve the mixed variable and multi-objective and multi-discipline problem can be seen as a comprehensive method for structural optimization without any limitations on the number and type of variables and objectives.

338 Topology Optimization of Elastomeric Gels with Internal State Variable Dependancies in the Sensitivity Analysis

Jorge Barrera Cruz, Kurt Maute

Research on soft, active materials have been increasingly growing in recent years; growth driven by potential applications that leverage their unique properties, such as a wide range of stimulants, lage deformations, and high motion complexities. Recent work in this area includes not only the development of new materials and innovative technologies, but also more complex and robust mathematical models that better describe their physics. In this paper we introduce a shape and topology optimization approach for finding the spatial arrangement of stimuli-responsive elastomeric gels. We exploit the ability of elastomeric gels to swell upon exposure to a solvent to design actuators that deform from an initially flat/simple plate into a curved/desired structure. The highly nonlinear chemo-mechanical response of the gel is described by a mathematical model that advances in time through an internal state variable that represents the swelling state of the gel. In addition, we introduce a formulation for the computation of the sensitivities of using the adjoint method for problems which formulations include dependencies on internal state variables. The proposed optimization process is studied with numerical examples where the objective is to find the material layout such that the active composite assumes one or more target shapes upon activation. The design studies demonstrate the ability of the proposed optimization method to yield a highly resolved description. of the optimized material layout that can be realized by 3D printing. As the complexity of the target shape increases, the optimal spatial arrangement of the material phases becomes less intuitive, highlighting the advantages of the proposed optimization method

339 An introduction to the OTI method to efficiently compute n-order derivatives

Mauricio Aristizabal, Manuel Garcia, Harry Millwater

Computation of derivatives is a current necessity for a wide variety of problems. First-order derivatives are a common requirement for applications such as optimization and sensitivity analysis. Some methods demand higher-order derivatives. However, its computation is usually avoided due to its complexity and lack of accuracy. This work presents a new number system, called order truncated imaginary (OTI) numbers, which serves as a method to compute n-order derivatives of multivariable functions, and it is based on Hyper-complex number systems. The method consists of imaginary directions that obey a multiplication rule that cancels out the terms with order greater than a specified value n. As a consequence, when a function is evaluated using a particular OTI number, the result is another OTI number that contains all derivatives up to n-order within its imaginary directions. A sparse computer implementation of the OTI numbers with operator overloading is developed. Two cases of study are presented for comparison purposes: (i) a sensitivity analysis to a finite element problem and (ii) computation of high order derivatives to a generic multivariable function. The method inherently produces exact derivatives and the accuracy is limited by the machine error. Compared with other methods, the OTI methodology is both time and memory efficient, as well as simple to use. However, for already existing programs, modifications at the source-code level should happen in order to include the methodology. The method opens the possibility to use high-order derivatives in applications where it was not possible before and creates an opportunity to develop new methods based on OTI numbers.

340 Parallel Constrained Efficient Global Optimization for Deterministic and Probabilistic Problems

Anirban Basudhar

Simulation-based design has evolved significantly in the past few decades. While the computing resources have advanced, model complexity has also increased considerably to capture the physics in greater detail. Therefore, reducing the number of expensive samples needed to obtain an optimal design is very important. Also, parallel computing has now become widely available, making the simultaneous selection of multiple samples desirable for any optimization algorithm.

Efficient global optimization (EGO) has become a very popular method since the late 1990s, but it only selects one sample per iteration and is unsuitable for parallelization in its original form. Different approaches to overcome this issue have been proposed, such as the Kriging-Believer, Constant Lier, as well as Pareto-based methods. However, there is scant literature pertaining to parallel sampling for constrained EGO, especially in the context of reliability-based design optimization (RBDO).

This work will present a Pareto-based parallel constrained EGO method for deterministic optimization and for RBDO. A guidance function based on proximity to the limit state will be used in the case of RBDO. A classification method will provide the total probability of feasibility (Pfeasible) of all constraints. Pfeasible will be used as one additional objective (irrespective of the number of constraints) to define a multi-objective problem for locating the samples. One of the infill criteria in sequential constrained EGO is to maximize the product of the expected improvement (EI) and Pfeasible. However, either of the two terms may dominate the other. The proposed approach will mitigate this issue by considering the Pareto front with trade-off between the two criteria. Also, instead of treating EI as an objective, it will be decomposed in two functions (prediction mean and variance), as EI may not always balance exploration and exploitation. Examples validating the proposed method will be presented.

341 Buckling optimization design of grid-stiffened shell considering numerical global and local buckling mode with machine learning process

Kook Jin Park, Masakazu Kobayashi

In this research, shape optimization of grid stiffened cylindrical shell under compressive axial load is performed to enhance the structural buckling resistance. Spacing and angle of stiffener, shell thickness and stiffener cross-section properties are considered as design variables. Buckling loads are obtained by finite element calculations using global/local coupled strategy with detailed model instead of considering each buckling mode separately. It needs to classify global and local buckling load for dealing with them as different objectives. Machine learning is used to distinguish each mode. Critical buckling loads and mass are considered as objective functions. Each buckling mode for thousands of cases are surveyed and converted as image, then it is used to build neural network for image recognition. Trained network to distinct buckling mode is used to extract smallest global and local critical buckling loads from numerical analysis results. Particle Swarm Optimization(PSO) is used to solve optimal problem instead of using gradient-based method, because it is required to consider misclassified cases of global and local modes which leads to imprecise results. Design candidates which are called as particle have their position in search-space, and particles are accelerated by exchanging information of critical buckling loads and structural mass with the other particles. Coefficients to determine particles velocity are surveyed by sensitivity analysis of design variables. The proposed method is further validated by comparing with PSO without classifying of buckling types.

342 Efficient Metamodeling Strategy using Multivariate Linear Interpolation for High Dimensional Problems

Kyeonghwan Kang, Ikjin Lee

Metamodeling method has been widely used to solve engineering problems which require significant computation, and there have been a large number of studies to propose efficient metamodeling methods in the last two decades. However, researches on practical metamodeling method dealing with high dimensional design space are insufficient. There sometimes exist high dimensional, expensive and black-box (HEB) problems, and handling these HEB problems with metamodeling method is challenging because of computational burden and complexity. In this paper, the efficient metamodeling strategy is proposed to handle HEB problems. The proposed strategy decomposes high dimensional design space into multiple less dimensional design spaces based on the coefficient of the multivariate linear interpolation equation. After the decomposition, sub-metamodels are generated using a sequential sampling method in each design space, and the final metamodel is constructed using these sub-metamodels. Numerical and engineering examples verify that the proposed strategy remarkably reduces required number of samples to satisfy the specified target accuracy compared to existing metamodeling methods.

344 Fast level set topology optimization using a hierarchical data structure

Carolina Jauregui, Alicia Kim

Using the level set method in topology optimization has several advantages, such as being able to handle complex topological changes and having a crisp definition of the boundary. However, a common criticism is that they tend to be slower in convergence than the traditional density-based approach. One reason for this slowness is attributed to having to search through grid points, such as when updating the level set functions and finding the nearest neighbor of a grid point. For example, a popular method for updating the level set function, the Fast Marching Method, has an algorithm of O(NlogN) because it uses a sorted binary tree as the data structure for storing grid values. This becomes very costly and slow as the number of grid points (N) increases. This paper will show that the efficiency of the level set method can be substantially improved by using a hierarchical data structure designed to take advantage of the level set methods unique characteristics.

The hierarchical data structure is a volumetric dynamic grid that is similar to B+ trees and allows for the efficient storage and manipulation of sparse volumetric data. By arranging blocks of the grid into a hierarchical structure that resembles a B+ tree, it can be shown that the structure can support fast random, sequential, and stencil access (average O(1)) to the grid data. This fast access speeds up the level set update and associated computations such as calculating the normal at the boundary. The presentation will demonstrate the efficiency of the level set topology optimization method with the hierarchical data structure for a range of problem sizes and the convergence will be compared against typical level set topology optimization results.

345 Fast Procedure for the Optimization of Stiffened Shells with Cutouts Reinforced by Curvilinearly Stiffeners

Peng Hao, Yangfan Li, Kuo Tian, Bo Wang

An efficient optimization framework of cylindrical stiffened shells with reinforced cutouts by curvilinear stiffeners is proposed in this study. Firstly, an adaptive method to determine the near field around the cutout and far field away from the cutout is presented. Then, a novel hybrid model is established to reduce the computational efforts of nonlinear post-buckling analysis: the Numerical Implementation Asymptotic Homogenization Method is used to smear out the stiffeners in the far field, and curvilinear stiffeners are adopted to improve the loading path and thus local stiffness of the near field, which can provide a type of flexible stiffener configurations for cutout reinforcement. After that, the optimization of curvilinear stiffeners is performed by a novel bi-level strategy based on the hybrid model. In the first level, a stiffener distribution function is utilized to reduce the number of active variables, and then stiffener layout, stiffener number and section profile are optimized simultaneously. In the second level, the stiffener number and section profile are held constant, and local optimization is then performed for each curvilinear stiffener location. Illustrative example demonstrates the effectiveness of the proposed framework, when compared with traditional optimizations.

348 Fast dynamic analysis and optimization of beam-type structures based on Parametric Reduced-Order Model

Li Yuwei, Wang Bo, Hao Peng, Zhou Yan, Zhao Yang

Dynamic numerical simulation of large-scale complicated beam-type structures is unavoidable in modern engineering calculations; however, the inherent nature of the models often leads to unmanageable demands on the computational resources. The model reduction method aims to reduce this computational burden by generating parametric reduced-order models (ROMs) that are faster and cheaper to simulate, yet accurately represent the original structures behavior. Therefore, a novel parametric reduced order model is proposed to determine the natural frequencies of the beam-type structures in this study, which is established by using a reduction basis along with the polynomial interpolation function (PIF) depends on a set of parameters. The basic idea is to translate the displacements of FEM nodes in each cross section into a small amount of nodes with a few generalized DOFs. Moreover, the proposed parametric ROMs has the ability to identify shell lobe-type modes and coupled modes. Then, a fast optimization framework for thin-walled cylinders is established based on the parametric reduced order model. Finally, numerical examples demonstrate the effectiveness of proposed method.

350 Efficient Optimal Surface Texture Design Using Linearization

Chendi Lin, Yong Hoon Lee, Jonathon Schuh, Randy Ewoldt, James Allison

Surface textures reduce friction in lubricated sliding contact. This behavior can be modeled using the Reynolds equation, a single partial differential equation (PDE) that relates the

hydrodynamic pressure p to the gap height h. In a previous study, a free-form texture design optimization problem was solved based on this model and two competing design objectives. A pseudo-spectral method was used for PDE solution, which was treated as a black box in the optimization problem. This optimization implementation did not exploit model structure to improve numerical efficiency, so design representation fidelity was limited. Here a new strategy is introduced where design representation resolution and computational efficiency are both improved. This is achieved by introducing a new optimization variable involving both pressure gradient and the cube of gap height at each mesh node location, and simultaneously solving the flow and texture design problems. This transformation supports linearization of the governing equations and design objectives. Sequential Linear Programming (SLP) is used with the epsilon-constraint method to generate Pareto-optimal texture designs with high resolution and low computational expense. An adaptive trust region is used, based on solution improvement, to manage linearization error. The method presented here has two distinct advantages over the earlier non-linear programming strategy: 1) increased design fidelity (each node of the pseudospectral mesh is a design variable), and 2) significantly reduced computational cost. Comparing to the non-linear programming implementation, the solution converged to a set of slightly suboptimal points (maximum 25% objective function degradation when normalized apparent viscosity is 0.5, and moderately better when normalized apparent viscosity is 0.2), but results in significant improvement in computational speed (8.4 times faster).

351 Mixed variable Structural optimization: toward an efficient hybrid algorithm

Pierre-Jean Barjhoux, Youssef Diouane, Stéphane Grihon, Dimitri Bettebghor, Joseph Morlier

Designing a structure implies a selection of optimal concept and sizing, with the aim of minimizing the weight or production cost. In general, a structural optimization problem involves both continuous variables (e.g., geometrical variables, ...) and categorical ones (e.g., materials, stiffener types, ...). Such a problem belongs to the class of mixed-integer nonlinear programming (MINLP) problems. In the work presented here, we will specifically consider a subclass of structural optimization problems where the categorical variables set is non-ordered.

According to our knowledge, the proposed solutions regarding MINLP problems are often based on turning categorical variables into continuous ones or, conversely, by transforming the continuous space into a set of integers. Once the problem is transformed, the objective function is optimized using nonlinear programming techniques such as branch and bound algorithms (B&B), genetic algorithms, optimality criteria methods or level sets methods. However, such solutions are deficient for the present case of a MINLP problem involving non-ordered categorical set: the means to achieve such variables transformations are not always adapted to the considered categorical variables, and large scale problems are not treated efficiently because of the combinatory complexity.

To facilitate categorical variables handling a new feature is introduced in this article: design catalogues are used as a generalization of the stacking guide used for composite optimization. From this new feature, a specific formulation of the MINLP problem is drawn and different ways of converting variables are investigated giving rise to new methodologies exploiting bi-level and B&B techniques.

These methodologies are tested on a 10 bars truss optimization test-case inspired from an aircraft design problem, consistent with the level of complexity faced in the industry, and bearing in mind that the process has to perform on large size problems.

352 Stress topology optimisation for architected material using the level set method

Renato Picelli, Raghavendra Sivapuram, Scott Townsend, H. Alicia Kim

This paper presents a stress-based level set topology optimisation method applied to microstructural design of architected material. Microscopic architected material systems are of interest due to the rise of additive manufacturing. Multiscale topology optimization leads to small members that may be more prone to high stress. The main contribution herein will be the combination of microstructural optimization with a von Mises stress p-norm functional. This type of function has been used to address the local nature issue of stress in macroscale design, approximating the maximum stress in the structure with a single function. The p-norm stress shape sensitivities will be presented using the material derivative method. The proposed level set method formulates a sub-optimization problem in each iteration and uses mathematical programming to obtain the optimal boundary velocities. The Ersatz material approach is used to link the level set method with the finite element structural analysis. First, numerical results for the macroscale are presented to show that stress concentrations are removed. Finally, a microstructural stress analysis based on the homogenization method is devised to reduce stress levels in microstructural topology optimization.

353 Virtual-Temperature-Method Based Formulation of Topology Optimization for Design of Cast Parts

Quhao Li, Wenjiong Chen, Shutian Liu

Apart from the functional requirement, the manufacturing process constraints become increasingly important in the structural design by employing the topology optimization method. This paper presents a novel method, Virtual-Temperature-Method based formulation, for topology optimization design of cast parts considering the molding constraint which require without interior voids and undercuts. A virtual thermal diffusion problem is appropriately defined and a global thermal constraint is added in the optimization model for guarantying the castability of the structural shape. The parting directions, unidirectional or multi-directional, are modeled by modifying the heat dissipation boundaries and the material properties. This method does not require an optimization process to start from a feasible initialization and can be applied almost in any topology optimization problems. Finite volume method is used to solve the steady-state heat equation and a parametric formulation of the conductive coefficient is given. Several topology optimization examples of cast parts are provided to illustrate the validity and the effectiveness of the proposed method.

354 A Novel Parameterization for the Topology Optimization of Metallic Antenna Design

Qi Wang, Renjing Gao, Shutian Liu

The metallic antenna design problem can be treated as an optimization problem to find the optimal distribution of conductive materials within a design domain so that the desired response of the antenna can be enhanced. In this paper, a novel parameterization with self-penalization scheme, which is based on a Tangential interpolation function and an adaptively Increasing Penalty-factor Strategy (TIPS), is proposed for the topology optimization of metallic antenna design. The topology description is based on the material distribution approach. And a tangential interpolation function is proposed to associate the material resistance with design variables, where the material resistance is expressed in the arctangent scale and the arctangent resistance is interpolated with the design variables using the rational approximation of material properties (RAMP). Using examples of antenna topology optimization based on the proposed tangential interpolation function, the problem of gray scale elements in the design results is illustrated and one of the reasons for that problem is explained. In order to eliminate the remaining gray scale elements, a strategy with adaptively increasing penalty factor during the optimization process is proposed, by which binary results can be directly obtained.

355 Topology optimization method for layout design of stamping structures with flanging

Shutian Liu, Yunfeng Luo

Adding flanges on the boundaries of the stamping parts is widely used reinforcement measure in thin-walled structures. Existence of these flanges may change the optimal topology relative to the structures without flanges. Thus, it is important to develop a method for designing the layout of the flanged structures. In this paper, A topology optimization method based on the "coating method" proposed by Sigmund in 2015 for designing infill-based components is proposed to design Stamping structure with flanging. In the present method, the structural flange is equivalent to a high stiffness material as the "coat" in coating method. The compliance topology optimization of the flanged structures with stress constraints and manufacturing constraints is considered. Several topology optimization results are obtained for different stamping process parameters. Numerical and experimental results show that the optimal structures obtained by the new method have better mechanical behavior than those obtained by the traditional topology optimization methods.

356 Topology optimization of damping layers in plate structures subject to impact loads for minimum residual vibration

Kun Yan, Gengdong Cheng

Many engineering structures are subject to impact load in their service life. The vibration response after impact is known as the residual vibration. For many precision mechanical systems, excessive structural residual vibration is of important concern. For minimum residual

vibration, this paper studies optimum distribution of damping material in plate structures subject to impacts by using topology optimization method. An integrated square performance index measures the residual vibration response globally and is used as the objective function. In this paper, the calculation of the objective function is simplified greatly with Lyapunov's second equation. Note that, the residual vibration (free vibration) response depends on the initial excitations, which are the vibration state at the end of the forced vibration responses induced by the impact load, which makes the sensitivities of the objective with respect to design variables difficult to calculate. To overcome this difficulty, the sensitivity analysis combines two existing methods, they are, the method proposed by Arora et al. and our early proposed method in the form of Riccati matrix equation. To make it more efficient, an adjoint variables method is further extended. For the topology optimization, the artificial element densities of damping material layer meshed by FEM are taken as topology design variables and updated by the MMA optimizer, and the limitation of damping material volume is used as the constraint. The influences of several factors, including the duration, time-profile and location of impact and boundary conditions of structure, to the optimum designs are discussed. Several numerical examples are carried out to verify the proposed approach.

357 Sustainable seismic design of reinforced concrete frame structures with genetic algorithms

Panagiotis Mergos

Reinforced concrete (RC) structures play a vital role in protecting human societies from natural threats. On the other hand, they contribute significantly to greenhouse gas emissions that have been the dominant cause of the observed climate change. This is mainly due to cement that is responsible for roughly 8% of global CO_2 emissions. The previous observations underline the need for optimum structural design of RC structures that minimizes their environmental impact as well as vulnerability to natural hazards.

Early optimization efforts of RC structures set construction cost as design objective. It was not until rather recently that research studies examined design of RC structures for minimum environmental impact. However, the latter studies do not address seismic design of RC structures. This is the case despite the fact in many countries around the globe, including most of the top-10 countries in CO_2 emissions from cement production (e.g. India, Iran, Turkey, Japan), RC structures need to be designed against earthquake hazard.

This study employs genetic algorithms to derive and compare seismic design solutions of reinforced concrete frames for minimum environmental impact and construction cost. Designs for various design peak ground accelerations, material classes and material environmental impact scenarios are examined. In all cases, the seismic designs are conducted in accordance with both the traditional methodology of Eurocode 8, for all ductility classes, and the performance-based approach of fib Model Code 2010.

It is found that the adopted seismic design methodology and the design peak ground acceleration greatly influence embodied CO_2 emissions of RC frames. On the other hand, the CO_2 footprint is not influenced significantly by the applied concrete grade. It is also concluded that the minimum cost and minimum CO_2 designs are very closely related. This is encouraging because both objectives should be considered in the design procedure.

359 OPTIMIZATION AS A TOOL TO EXPLORE THE PHYSICS IN PARTICLE JET FORMATION DURING EXPLOSIVE DISPERSAL OF SOLID PARTICLES

M. Giselle Fernández-Godino, Frederick Ouellet, S. Balachandar, Raphael T. Haftka

Dense layers of solid particles surrounding a high energy explosive generate jet-like structures at later times after detonation. Conjectures as to the cause of these jet structures include: (i) imperfections in the casing containing the particles, (ii) inhomogeneities in the initial distribution of particles, (iii) stress chains within the particle bed during shock propagation and (iv) non-classical Rayleigh-Taylor and Richtmyer-Meshkov instabilities.
We hypothesize that (i), (ii) and (iii) produce initial variations that develop into jets. We characterize this variation as particle volume fraction (PVF), defined as volume of particles divided by the volume of particles and gas. Our goal is to explore what initial PVF variation would lead to the observed jet formation.
An optimization process will be carried out to determine the parameters of the initial PVF that lead to jet formation. An initial hurdle was to select an objective function that would represent such jets. After substantial analysis and numerical experimentation, we divide the space into angular sectors and measure the ratio of the number of particles between the sector with most and the one with fewest particles. The variables considered are the parameters of a three mode sinusoidal perturbation (amplitude, wavelength, and phase angle between modes). Initial trials showed that we can start with an initial perturbation with a ratio of 1.3, and grow it to a ratio of 3.9.
Substantial noise led to our focused noise reduction efforts. The magnitude of the noise was determined by deviation from perfect rotational symmetry in the measured objective functions for corresponding rotation prescribed in the initial perturbation. The cause of the noise was determined to be a combination of randomness in the initial position of the particles and the use of Cartesian coordinates for a cylindrically symmetric problem. This paper will include the measures taken to reduce noise and the optimization results.

360 Shape optimization of cross sections of composite beams for maximum buckling performance

Huu Dat Nguyen, Gang-Won Jang

In this investigation, the cross section of a thin-walled composite beam is optimized to maximize the buckling strength using shape optimization based on a finite strip method. This study is the subsequent research of the authors' recent buckling topology optimization of a beam cross section using a finite prism method. While the use of a finite prism method significantly reduces the cost of analysis compared to three-dimensional finite element method, optimized beam cross sections have difficulties from manufacturability point of view such as nonuniform wall thicknesses and complex reinforcing patterns. Moreover, topology optimization cannot deal with beams of laminated composites. In this study, a finite strip method is employed as an analysis tool by treating walls of a cross section as strips (or plates) of uniform thickness. The coordinates of vertices of a cross section are set as design variables while the design objective is given as the fundamental buckling eigenvalue. Because a finite strip method is based on a plate theory, it is easy to consider composite laminates in the optimization formulation such that the fiber angles can be also employed as design variables. To enhance manufacturability of composite laminates, the discretization of design variables for fiber orientation angles is taken into account. The optimization problem is formulated using the bound formulation which also treats mode switching phenomena of multiple eigenvalues. Depending on the length of a beam, the behavior of the lowest modes can be either global bending or local plate bending. Numerical examples with different design domains and various beam lengths are solved to show the validity of the proposed method.

361 Concept design of automotive body frame using higher-order-beam-based modeling method

Ngoc-Linh Nguyen, Gang-Won Jang

This investigation presents the beam-shell modeling of an automotive body to optimize global static or dynamic performances based on a higher order beam theory. The proposed beam-shell modeling method has high analysis accuracy, fast computation and easy implementation at the earliest phase of the design process when a detail model is not available. Although many researches on beam-based modeling methods have been conducted for vehicle structure designs, the accuracy of traditional beam methods is not high enough to be used in real applications. To resolve the inaccuracy issue of beam modeling methods, this study employs beam elements using a higher order beam theory. Higher order beam elements employ cross-sectional deformations as additional degrees of freedom as well as conventional six rigid body deformations (three translations and three rotations). To derive higher order cross sectional deformations, numerical methods using cross-sectional beam frames are used. Although a higher order beam theory can account for the accurate stiffness of straight or moderately curved beams with generally-shaped cross sections, the flexibility at a joint connecting beams is still difficult to accurately predict, so shell elements are used for the joint modeling. Therefore, the present concept model of an automotive frame consists of higher order beam elements for straight/curved beam members and shell elements for joints. Special attention is given to the connection technique between higher order beam elements and shell elements; the continuity of translation displacements and rotation angles with respect to the normal axis at the common interface between beam and shell parts is matched to derive the interface matching conditions. In order to minimize the use of shell elements for joints, the analysis accuracy of the proposed beam-shell modeling is checked by varying size of the joint region and comparing its static/dynamic results with those obtained by pure shell elements. Fi

362 Optimal topology design of locally resonant metamaterial with plate-like resonator

Jaesoon Jung, Seongyeol Goo, Semyung Wang

This paper presents a topology optimization of locally resonant metamaterial (LRM). The LRM is constructed by base plate, plate-like resonator and frame supporting the resonator. The local resonance of the plate-like resonator makes stop band that is frequency band with no wave propagation, at low frequency regime. Using the stop band characteristics, LRM effectively attenuates low frequency sound and vibration. In order to maximize the performance of the LRM, topology optimization is applied in this paper. The plate-like resonator is considered as a design domain and stop band width is maximized with satisfying volume constraint. Design sensitivity formulation is derived for stop band width and method of moving asymptote (MMA) optimizer is used. The optimized design shows broader stop band comparing with the original design.

365 Isogeometric Shape Design Optimization of Periodic Cellular Materials with Negative Poisson's Ratio

Myung-Jin Choi, Myung-Hoon Oh, Sehyun Kang, Seonho Cho

For the shape design of inner holes in periodic cellular materials that have negative Poisson's ratio (NPR) induced by deformation-induced pattern transformations, a continuum-based shape design sensitivity analysis (DSA) and optimization method is presented. The existing circular hole model based on elastic buckling suffers from the direction uncertainty of pattern transformations due to its instability. Also, the circular hole model has the difficulty to represent the NPR in tension since the ligaments do not have sufficient moments for pattern transformations. Although the existing elliptical hole model shows the NPR behaviors in both compression and tension, it also has difficulty in practical uses due to stress concentration on narrow ligaments, which significantly reduces the stiffness and durability of structures. Therefore, using shape design optimization method, this paper pursues the following objectives: (i) increasing the absolute value of NPR, (ii) mitigating stress concentration, (iii) increasing the overall stiffness of structures. In numerical simulations, under the total Lagrangian formulation, a mixed variational formulation is presented, considering nearly incompressible hyperelastic materials. Finite displacement, finite strains, and material nonlinearities are included in the analysis model. Using the isogeometric analysis (IGA), a subdivision property of the NURBS basis functions is employed to independently interpolate the hydrostatic pressure and displacement field with equal higher-order basis functions. In the shape DSA, the material derivative concept is utilized, and displacement loading condition is considered. The superior accuracy of IGA in the response analysis and the DSA is observed through the comparison with the results of FEA. Various numerical examples are presented for the shape design optimization of NPR materials including curved structural domain.

366 Conceptual design of displacement magnifying mechanism considering epistemic and aleatory uncertainty

Makoto Ito, Nozomu Kogiso

This study shows the optimization of the displacement magnifying mechanism with uncertainty as component of our proposed high-precision smart space structural system. In the past study ([1] Furutani, et al.), the mechanism is optimized as a kind of compliant mechanism to reduce the number of parts. The study showed that there is the trade-off between each dimensions and the tip displacement as the mechanism performance. However, the actual mechanism should consider uncertainty. Especially, the manufacturing uncertainty has significant impacts on the performance. Moreover, the number of experiments which should be needed to investigate the manufacturing uncertainty is limited due to the various reasons. Accordingly, this study applies the optimum design considering uncertainty. The manufacturing uncertainty is applied to the probabilistic distributions and the lack of knowledge of the distributions is regarded as epistemic uncertainty. The optimization of the displacement magnification mechanism is applied to reliability-based design optimization (RBDO) with considering epistemic uncertainty. RBDO considering epistemic uncertainty is developed as the robust design method in the past study ([2] Ito, et al.). In this case, this study will achieve the robust design for the lack of information of the manufacturing uncertainty.

[1] Furutani, et al., Trade-off analysis of displacement magnification mechanism based on multi-objective optimization, 60th Aerospace science and technology symposium, Hakodate, Japan, (2016), 3H08 , (in Japanese).

[2] Ito, et al., Robust design method considering information uncertainty based on hyper parameter estimation, ACSMO2016, Nagasaki, Japan, (2016), 2E1-2.

367 Geometric and Material Optimisation of Bend-Twist Coupled Wind Turbine Blades

Terence Tacquart, David Langston

This work explores the design of geometrically and materially bend-twist coupled wind turbine blades that passively react to their environment in order to decrease structural loads. The challenges associated with the design and manufacture of cost effective blades are considerable. To ensure that the cost of wind energy remains competitive with other energy sources, blade designers must continually improve their designs in order to limit the increased fatigue and extreme loads as turbines increase in scale. Improvements in wind turbine technology has largely been incremental, delivering small improvements to proven technologies thus minimising risks. For turbine blades we have witnessed a progressive development of a classical blade configuration which may have potentially restricted the evolution of more novel blade designs.

In contrast to this incremental approach, we develop a new design and optimisation tool for wind turbines in order to open up the conventional design space and potentially provide new solutions to the complex structural design of blades. In particular, the concept of bend-twist coupling is revisited for large blades while considering both geometric and material coupling simultaneously with the help of state-of-the-art beam and shell models. For that purpose, a compact structural design parametrisation based on lamination parameters is employed in order to provide a unique means of exploring the non-conventional blade structural design space.

The final paper will provide a detailed description of our aero-structural optimisation approach as well as an applied case study based on a 7 Mega-Watt offshore wind turbine. Additionally, a comparison between the conventional and the bend-twist coupled designs will highlight the potential benefits and drawbacks associated with the newly proposed blade structural designs.

369 Convergence Strategy for Parallel Solving of Analytical Target Cascading with Augmented Lagrangian Coordination

Yongsu Jung, Namwoo Kang, Ikjin Lee

Analytical Target Cascading (ATC) is a decomposition-based optimization methodology which partitions a system into subsystems and coordinates targets and responses among subsystems. Augmented Lagrangian relaxation with Alternating Direction (AL-AD) has been widely used for the coordination process of both hierarchical ATC and non-hierarchical ATC, and in theory, it guarantees convergence under the assumption that all subsystem problems are convex and continuous. One of main advantages of ATC is that it can solve subsystem problems in parallel so that it can reduce computational cost by parallel computing. Some previous researches proposed Augmented Lagrangian coordination strategies for parallelization by eliminating interactions between subproblems. This is done by introducing a master problem and support variables or approximating a quadratic penalty term to make subproblems separable. However, our study claims that ATC using AL-AD does not guarantee convergence in the case of parallel solving. We tested geometric examples widely used in previous ATC researches, and showed that consistency constraint violation can oscillate, and problems start to blow up after many iterations. Our study found that, in parallel solving, conventional AL-AD causes mismatch in updating Lagrangian multiplier using targets and responses during iterations. Therefore, the Lagrangian multiplier may not reach the optimal point, and thus increasing penalty weight causes numerical difficulty in the AL penalty function approach. We propose a modified parallel AL-AD with sequential-updating Lagrangian multiplier. The proposed method uses an adaptive step size in updating Lagrangian multiplier which is independent of quadratic penalty terms and keep quadratic penalty terms at the initial value. Without introducing additional variables or master problems, the modified parallel AL-AD can achieve similar accuracy and convergence with much less computational cost, compared to conventional AL-AD.

370 A New Resilience-Driven System Design Considering False Alarms

Joung Taek Yoon, Minji Yoo, Byeng D. Youn, Yunhan Kim

In order to make engineered systems operate reliable for a specified period of time, many design methods have been developed. Most of them manipulate a passive design capacity, the stress level which an engineered system can withstand, for stated conditions (e.g. load, environment). However, they can be unreliable because of unexpected uncertainty factors such as human error, excessive load, initial defects. Recently, the resilience-driven system design (RDSD) has been proposed to make engineered systems adaptively reliable by incorporating the prognostics and health management (PHM) method. PHM tracks health degradation of engineered systems due to the uncertainty factors and provides health state information supporting decisions on condition-based maintenance. This study aims at proposing a new resilience-driven system design considering false alarms. A false alarm in PHM denotes an erroneous report on health state of an engineered system: faulty one as healthy one, or healthy one as faulty one. As false alarms can depreciate system availability instead of preventing system failures, they should be considered in resilient system design problems. At first, two types of false alarms in PHM are defined as a quantification method is described. Then, an engineering resilience measure is revised to incorporate false alarm rates via probabilistic approach. With the use of the revised resilience measure, the resilient system design is processed with three steps: (i) resilience allocation problem (RAP), (ii) reliability-based design optimization (RBDO), and (iii) system design. The effectiveness of proposed method compared to the original RDSD method is demonstrated with an electro hydraulic actuator (EHA) design problem.

371 Statistical Model Calibration and Validation of Elasto-Plastic Analysis in Pyrotechnically Actuated Devices based on Operating Mechanism

Hee-Seong Kim, Joo-Ho Choi, Nam-Ho Kim, Seung-Gyo Jang

Pyrotechnically Actuated Device (PAD) is a valve that triggers intended mission such as launching or deployment in the aerospace industry. It operates by instantaneous combustion of a propellant in the chamber, generating pressure to push the piston and triggers opening of the gas flow. Due to its critical nature, very high reliability is required but the evaluation is difficult, which is the reason that the computational model is usually employed. The model, however, consists of complex piston dynamics coupled by the combustion physics and piston-housing plastic deformation, which is often inaccurate in real applications unless calibrated appropriately. In this study, a comprehensive calibration is carried out based on the Bayesian statistics to develop the model that agrees with sufficient accuracy with real tests under a confidence level. The computational model involves piston dynamics at the system level that solves the piston motion due to the combustion pressure and frictional resistance by the housing. Two sub-models are built within: the combustion of the propellant that generates gas pressure and the elasto-plastic deformation of the piston and housing. Calibration is then conducted in two stages: at the first stage, elasto-plastic sub-model is calibrated against the quasi-static compression tests of the piston against the housing separately conducted for the calibration purpose. At the next stage, system model is calibrated simultaneously with the combustion sub-model by the actual operation tests of the PAD that measure the pressure history and piston motion. Once the calibration is made with success for the baseline model, it is applied to the similar other types of the PAD, and the simulation results are validated against their corresponding operation tests.

373 Boundary condition optimization of distributed mode loudspeaker to improve the sound pressure level performance

Hyun-Guk Kim, Semyung Wang

Flat panel speaker is based on the resonant multi-modal radiator invented by Ken Heron in Defence Evaluation and Research Agency. Originally, the resonant multi-modal radiator is designed to be used as the internal material for a helicopter. However, this radiator was used as the part of the flat panel speaker. Unlike a conventional cone-type loudspeaker, the sound pressure level of the flat panel speaker evenly distributed the mode of the structure over the frequency range. For this reason, a relatively uniform sound pressure level is seen over this frequency range. In order to design the flat panel speaker, a designer should consider material-type of the panel, the shape of the panel, number of the exciter, exciting force, and the boundary condition of the panel with an enclosure of loudspeaker.
In this research, the boundary condition of the panel was determined. The boundary means the surround that connects the panel to the enclosure. The surround could be expressed as a combination of the linear and rotational spring. For the realization of the elastic boundary condition, the linear and rotational elastic force terms are added to the external force vector. Because elastic force terms could be expressed as the product of the elastic matrix and displacement vector, linear system that have elastic-stiffness matrix is established. Using this model, the linear and rotational stiffness coefficient are optimized to minimize the standard deviation of the sound pressure level over the specific frequency range.

374 Large-scale three-dimensional topology optimization considering overhang limitations in 3-D printing

Yoram Mass, Oded Amir

Topology optimization deals with the automatic optimal repartition of a specific material, submitted to external loads and boundary conditions within a defined volume. As these algorithms can output relatively complex designs, additive manufacturing technologies, and specifically 3D printing, seem to be the perfect match to produce them. However, many of these technologies are limited to a maximal overhang angle and thus cannot manufacture overhang patterns without additional supports. The most immediate idea to alleviate this limitation is to integrate the supports in the design.

Several methods were developed in that spirit. As applying geometric constraints into a density-based topology optimization problem can be challenging, the main methods use a filtering approach. In Guest and Gaynors works as well as in Langelaars works, the existence of each element depends on whether it is properly supported. This filter is respectively applied globally and layer-wise. Both works report good printability and relative little drop in performance compliance in this case. The present work is the three-dimensional generalization of two methods we suggested recently, for which encouraging results in 2-D were obtained. In the first, an optimal truss was generated based on allowable directions, giving preferred locations for material distribution in the continuum problem. In the second, deformations caused by the layer-by-layer fabrication process were considered in the objective based on the material self-weight.

The advancement of these methods towards large-scale problems brings new challenges, arising for example from the complexity of the spatial geometries and from the need to reduce the computational burden of large-scale topology optimization. The proposed work will highlight the main results obtained as well as the quandaries faced to get them, and advise the best choice of parameters, while comparison with other existing approaches will also be discussed.

375 A lean method for local patch reinforcement using principal stress lines

Philipp Gebhardt, Eiko Türck, Thomas Vietor

Composite materials offers the possibility to design tailored laminates for a broad spectrum of applications such as airplane wings or monocoques in the automotive industry. Especially when carbon fiber reinforced plastic is used, parts with enormous performance can be designed. The downside of designing a laminate is the complexity of the task itself, as well as the price of the carbon fiber. Placing the expensive carbon fiber only at the necessary positions can help to reduce the costs of the parts and to increase the performance, specifically the stiffness, compared to a glass fiber laminate itself. Designing the laminated get even harder, an algorithm is needed to support the engineer in this task.

This paper will introduce a lean method using the principal stress line to locate the best position for carbon fiber patches using a Michell structure. The Michell structure is optimized for tensile and pressure forces. Unidirectional tapes have outstanding properties in fiber direction, but weak performance orthogonal to the direction of the fiber. Placing the unidirectional tapes along the Michell structure will load the tapes in an optimal way. First of all the algorithm will determine the principal stress lines connecting load and bearing. These will be used as a starting point for a Michell structure. The generated Michaell structure will be optimized to increase the performance. After the substructure is found, it will be mapped back into the original laminate. The new improved laminate will be compared with the original one, concerning weight, stiffness and pricing.

376 Topology optimization of turbulent flows with the RANS k-omega model

Cetin Batur Dilgen, Sumer Bartug Dilgen, David R. Fuhrman, Ole Sigmund, Boyan Stefanov Lazarov

The focus of this work is on the application of density based topology optimization to turbulent flow problems. Throughout the optimization process, steady-state incompressible Reynolds-averaged Navier-Stokes (RANS) equations are utilized for modeling the fluid flow. A numerical solution is obtained by employing 3D finite volume method combined with the SIMPLE algorithm for pressure-velocity coupling. Turbulence closure is achieved utilizing the two-equation k-omega model. An important novelty of this work is the utilization of automatic differentiation (AD) in reverse mode for obtaining exact sensitivities of the discrete system. It is found that AD tools significantly automatize the implementation of the exact adjoint with turbulence models, allowing for easy inclusion of new modeling features, boundary conditions and new physics. The advantages of the proposed methodology are demonstrated on several internal flow applications, and comparison to the commonly-used frozen turbulence assumption is provided. Furthermore, in order to accommodate high Reynolds number flows, the introduction of wall functions in the discrete adjoint RANS framework is demonstrated as well.

377 FDIPA_ GSDP - A Feasible Point Algorithm for General Semidefinite Programming with Applications In Structural Optimization

Jose Herskovits, Jean Rodolphe Roche, Elmer Bazán, Andrés Zúñiga

We consider nonlinear optimization problems with standard equality and inequality constraints, as well as semidefinite (SD) constraints on symmetric matrix-valued functions. SD constraints are involved in several structural optimization problems. This is the case of Free Material Optimization (FMO), that needs positive definite elementary elasticity matrices. Constraints on structural fundamental frequencies can be represented as (SD) constraints.

FDIPA_GSDP is a generalization of the Feasible Direction Interior Point Algorithm for nonlinear smooth optimization, FDIPA. FDIPA_GSDP makes iterations in the primal and dual variables to solve the first order Karush-Khun-Tucker optimality conditions. Given an initial interior point, FAIPA_GSDP generates a descent interior sequence, converging to a local solution of the problem.

Feasible iterates are essential in applications where the calculus of some of the involved functions requires the satisfaction of a set of so-called hard constraints. In FMO the elementary stiffness matrices must be positive definite to be able to carry out the structural analysis.

At each iteration, FDIPA_GSDP computes a feasible descent direction. A line search along this direction results in a new feasible iterate with better cost. The calculation of the search direction merely requires the solution of two linear systems with the same matrix.

Global convergence of the present algorithm to a stationary points is proved. We also describe our results of a set of Structural Optimization problems with different objective functions and constraints. All the problems were solved very efficiently without need of algorithm parameters tuning.

378 Density based topology optimization of turbulent flow heat transfer systems

Sumer Bartug Dilgen, Cetin Batur Dilgen, David R. Fuhrman, Ole Sigmund, Boyan Stefanov Lazarov

The aim here is to demonstrate a further extension of the already developed turbulent flow framework for density based topology optimization. The optimization considers fluid problems modeled by steady state incompressible Reynolds-averaged Navier-Stokes (RANS) equations. Turbulence closure is achieved utilizing the two-equation k-omega model, and the solution of the state problem is obtained using 3D finite volume framework where the exact gradients of the objective and the constraints with respect to the material density parametrization are obtained by the adjoint method. The implementation complexity of the exact adjoint is handled with the help of automatic differentiation (AD). The employment of AD allows for relatively easy inclusion of new physics, constraints and changes of the objective. These features are demonstrated in the optimization of heat transfer systems with turbulent flows where the adjoint solution is obtained without any simplifications, such as the commonly-used frozen turbulence assumption. The considered examples include internal manifold flow problems where multiple outlets are constrained such that specified mass flow rates and flow temperatures across the outputs are obtained.

379 Structural optimization with an automatic mode identification method for tracking local vibration mode

Shenyan Chen, Yanwu Zheng, Yanjie Liu

In aerospace structural design, the local mode of a certain panel, sometimes need to be improved to improve the dynamical characteristics of this area. To add stiffeners to the panel could increase the local modal frequency. In order to obtain the reasonable cross-sectional dimensions of the stiffeners, structural optimization with local mode constraints could help to solve this problem. However, the order of the local mode may change frequently with the variation of the cross-sectional dimensions of the stiffeners. As a result, optimization process which takes the certain order of modal shape as the constraint cannot obtain the desired solution. In order to solve this problem, a local mode identification technique is proposed, which can automatically update the constraint mode order. An optimization model with the continuous size variables with respect to the cross-sectional dimensions is established, in which the minimum weight and local modal frequency are considered as the objective and the constraint. The element strain energy ratio is used to identify the order of the local modal frequency. The ratio is calculated by comparing the sum of the strain energy of the elements in the stiffened panel with the strain energy of the whole structure. If the ratio is greater than a specific value, the local mode is identified and the order of the local mode frequency will be updated during the optimization process. Then, Two-Level Multipoint Approximation method is applied to search the optimum. An optimization system which adopts the proposed local mode identification technique is developed based on Patran environment. The system was firstly applied in a reinforced plate to verify the feasibility of the proposed method. It was further used to improve the local frequency of a panel within a satellite. The results showed that the optimization process could be implemented successfully and optimized stiffeners could be obtained for the practical engineering problem.

380 Structural Optimization with an Automatic Payload Mass Adjustment

Shenyan Chen, Yijie Hu

As a spacecraft, it usually consists of mission-specific payloads and a platform, or a collection of subsystems. Due to the complexity of the mechanical environment for spacecraft and the increasingly higher requirements on their performance and light-weight design, structural optimization gradually became an indispensable step in structure design.
During the optimization process, minimization of global mass is traditionally adopted as the objective in which the payload mass is usually fixed. However, there is a possible situation

that the global mass is critically determined by the launch capacity and the payload mass can be adjusted with the change of the structural weight. In view of the important role of payload in the spacecraft design, it might be meaningful to consider the variable payload mass and investigate its effect to the optimization results.

In order to solve this problem, the total mass of a spacecraft is firstly divided into three parts: the variable structural mass (VSM), the variable payload mass (VPM) and the other invariant mass. Then, the optimization model is established by taking the minimum VSM as the objective. We want to adjust the VPM with the variation of the VSM, while the total mass is kept as a constant. A new optimization process is developed to adjust the VPM after each iteration so that the constant total mass could be satisfied. The general finite element program Nastran is adopted to perform the structural analysis and sensitivity analysis, and the two-level multipoint approximation algorithm is applied as the optimizer. The proposed method was firstly applied in the 25-bar example. The results showed that the ratio between the payload mass and the total mass could be increased significantly. This method was further used in a satellite model to demonstrate the feasibility and effectiveness in practical structure design.

383 Parametric Modeling and Optimal Design of Space Tubular Extendable Booms via a One-dimensional Unified Formulation

Yi Hu, Yong Zhao, Zhouhui Tuo, Jie Wang

The increasing demand for greater satellite mission capabilities has led to the need for lighter, stronger space deployable structures within the limited packaged volume. Tubular extendable booms, characterized by small stowed volume, light weight and large magnification ratios, have been widely used in small satellite missions, especially in cubesat missions. However, the deployment accuracy of these booms remains to be carefully analyzed and optimized, as the actual parameters are nonlinear. This paper presents a simple and general methodology for parametric modeling and optimal design of typical tubular extendable booms via a one-dimensional unified formulation. Using enhanced capabilities of refined beam elements, we obtained parametric models with remarkable reductions in computational costs are obtained to detect shell-like solutions for the booms. Then optimal design of the boom structure is easily achieved, as changes to the cross-section only alter the integration domain during analytical procedure. Finally, the optimized mechanical performance of these tubular extendable booms (including boom bending/torsional stiffness, relative tip displacements) is evaluated and compared under various loading conditions. Comparisons have shown that the structural stiffness of storable tubular extendable member (STEM) boom could be significantly improved by its proper configuration/material improvement. While the collapsible tube mast (CTM) boom and triangular rollable and collapsible (TRAC) boom have increased their anti-bending capabilities. All these improvements are of instructive significance in structural design of these tubular extendable booms, make the booms better at performing deployment tasks.

384 Multi-objective reliability-based design optimization for vehicle structures coupled process-performance

Huile Zhang, Guangyong Sun, Guangyao Li, Qing Li

Light weight and crashworthiness design have been two main challenges in the vehicle industry, which often conflict with each other. To achieve light weight while improving the crashworthiness, design optimization techniques have been widely used. However, traditional crashworthiness optimization and process optimization are always performed respectively. That is, few process requirements are considered in the crashworthiness design which may lead to non-optimal or even impractical process characteristics, and vice versa. Meanwhile, most of the energy absorbing members in vehicle body are fabricated by stamping process which will cause non-uniform thickness, residual strains and stresses, especially for those steel with high ductility and strength. Furthermore, the stochastic uncertainties associated with the material properties, process and geometry are propagated and represented to process and crashworthiness responses. In other words, a deterministic optimization could lead to unreliable designs. To address these issues, a multi-objective reliability-based design optimization coupled process-performance was proposed to optimize the double-hat thin-walled structure (DHTS). In which, a finite element-based sequential coupled process-performance approach was first developed to simulate the forming and crashworthiness characteristics of the DHTS in a manner that the material properties, process parameters and component geometry can propagate from forming simulations to crashworthiness simulations. Then, the metamodel technologies were adopted to approximate the responses. Finally, the MOPSO approach, coupled with MCS, was employed to seek optimal reliability solutions. The optimal results show that the proposed method was not only significantly improved the formability and crashworthiness, but also capable of enhancing the reliability of Pareto solutions.

385 Conceptual design of aircraft structure based on topology optimization method

Guanghui Shi, Yupeng Zhang, Dongliang Quan, Dongtao Wu, Chengqi Guan

Compared to traditional aircraft/missile design, high-speed aircraft design is more challenging since the corresponding aerodynamic shape is totally dependent of the mass ratio of the high-speed structure. In order to guarantee the feasibility of the overall design program, topology optimization methods are often adopted in conceptual design stage. In the problems, in addition to refined finite element (FE) model, multi-constraints, including mass, x/y/z center of gravity, maximum displacement, first order frequency, will also be considered. However, this will inevitably lead to large computational efforts in the solution process (huge numbers of design variables and constraints).

In the present work, an efficient topology optimization method is proposed for high-speed aircraft design. This is achieved as follows: first, we divide the overall structure into several substructures, where the number of design variables and degrees of freedom in finite element analysis can be reduced sufficiently. On each substructure, topology optimization is pre-carried out to identify the rational design range of each constrain for feasible purpose. Then, cabins constrains including quantitative and non-quantitative design indicators will be decomposed from overall structure design parameters. According to above crude results, topology optimization will be carried out to obtain the optimal design. Numerical examples of x-43 aircraft show that the proposed method can obtain good solutions to high-speed aircraft design problems with feasible overall design program and that this can be achieved using significantly fewer design variables compared traditional methods. Furthermore, the problem of large computational efforts in the solution process can also be solved under the recent Moving Morphable component (MMC) solution framework. We also discuss this research aspect in our work.

386 Topology and sizing optimization of nonlinear viscous dampers and their supporting braces for the displacement control of yielding frame structures

Nicolò Pollini, Oren Lavan, Oded Amir

In recent years, fluid viscous dampers proved to be effective for the reduction of displacements and total accelerations in structures subject to earthquakes. Their efficiency and cost is strongly related to their size and distribution in the structure. Thus, several methodologies based on optimization were developed for the design and allocation of viscous dampers for seismic retrofitting. Many of those considered linear viscous dampers. In practice however, nonlinear dampers are widely used.

In this work, nonlinear fluid viscous dampers are distributed in yielding frame structures and simultaneously sized by an optimization algorithm. The optimization-based design is extended also to the structural elements. We consider each damper in series with its supporting brace. A fractional power-law describes the nonlinear force-velocity behavior of the damper, and a linear spring with finite stiffness models the supporting brace. We consider predefined potential locations for dampers in the structure, and a limited number of dampers size-groups whose properties are also defined based on optimization. Binary variables describe the dampers existence and size-group association, continuous ones the properties of each size-group. A realistic cost function is minimized, while constraints are imposed on inter-story drifts. These are evaluated with nonlinear time-history analyses considering the structures subject to ground accelerations.

The problem is first formulated as a mixed-integer programming problem and solved with a genetic algorithm. To reduce the computational cost, the problem is reformulated with continuous variables only and solved with a sequential linear programming approach. The gradients are calculated consistently with the discretize-then-differentiate adjoint variable method. Final discrete designs are achieved by means of material interpolation schemes (e.g. SIMP, RAMP).

The advantages of the proposed approach are demonstrated with numerical examples.

387 Implementation of Turbulent Flow in Topology Optimization

Ram Ranjan, Matt Pearson, Brian St. Rock

In the last decade, topology optimization (TO) methods have emerged as a promising tool to develop novel conceptual design of engineering components. For flow components, however, these methods are still limited to low Reynolds number, laminar flow problems. This limits their applicability to practical design problems of industrial relevance. To overcome this limitation, turbulent flow models need to be included in the topology optimization framework. In this paper, the implementation of turbulent flow equations in density method TO is presented. The standard k-epsilon turbulent flow model is considered for TO implementation. The suitability of this approach is demonstrated for a simple 90 deg flow elbow design. It is shown that without the correct boundary conditions of k (turbulent kinetic energy) and epsilon (turbulent energy dissipation) on the evolving solid-fluid topological boundaries, the prediction of pressure drop and axial velocity in the pipe is two orders of magnitude smaller than CFD predictions. Also artificial velocities in the solid region are noted. With the turbulent boundary condition implementation, the axial velocity and pressure drop at the pipe center line are within +/-20% of the analytical and CFD predictions. Finally, an elbow design with turbulent Reynolds number (10,000) is presented.

389 An Augmented Sequential Optimization and Reliability Assessment for Uncertainty-based Multidisciplinary Design Optimization

Jafar Roshanian, Ali Asghar Bataleblu, Benyamin Ebrahimi, Ali Akbar Amini

Incorporating inevitable uncertainties in the multidisciplinary design optimization (MDO) of complex engineering systems has become a necessity to increase the system performance while meeting the reliability and robustness requirements. Despite tremendous efforts have been made in the field of Uncertainty-based MDO (UMDO), computational efficiency is still a significant challenge. Sequential optimization and reliability assessment (SORA) has made great efforts to improve computational efficiency by decoupling Reliability based Design Optimization (RBDO) problem into sequential deterministic optimization and reliability assessment as a single-loop method. The reliability assessment is only conducted after the deterministic optimization to verify probabilistic constraint satisfaction. In this paper, in order to further improve computational efficiency and extend the application of the current SORA method, an Augmented SORA (ASORA) approach is proposed by refraining from reliability assessment for satisfied probabilistic constraints in each cycle until all probabilistic constraints are satisfied. Therefore, the proposed approach requires much less function evaluations of the probabilistic constraints in each cycle compared with the original SORA method. The validation and efficiency of the proposed ASORA approach is illustrated through some single-disciplinary and multi-disciplinary mathematical examples.

390 Metamodel-based Multidisciplinary Design Optimization of a General Aviation Aircraft

Jafar Roshanian, Ali Asghar Bataleblu, Mohammad Hosein Farghadani, Benyamin Ebrahimi

Computational burden is still a significant challenge in the in multidisciplinary design optimization (MDO) of complex engineering systems. This challenge can be arising from the curse of dimensionality of the design space and the multiplicity of disciplines involved in the design problem. Tremendous efforts have been made to improve the computational efficiency, especially in the field of MDO. Meta-modeling is one of the powerful tools to facilitate this problem and has been received increasing attention in the past decades. Meta-models are

used to provide simpler models instead of the complex original models and by admitting a small percentage of error reduces computing time of the problem. Kriging meta-model, due to its high efficiency in medium dimension problems has been attracted the attention of many researchers. Due to lack of continuity in the complex design problems, creating a comprehensive and appropriate meta-model with acceptable accuracy to cover the entire design space is difficult and almost impossible. This paper proposed a strategy to improve the accuracy of the created meta-models using the elimination of outlier data from sampled points and re-designing the effective Kriging meta-model parameters. The proposed strategy is applied to the conceptual design of a General Aviation Aircraft (GAA) using MDO methodology and appropriate Kriging meta-model. Meta-models of the design disciplines including propulsion, aerodynamics, weight and sizing, performance criteria and stability disciplines are created and integrated based on Multidisciplinary Design Feasibility (MDF) structure to improve the aircraft performance. The gross weight of the aircraft and cruise phase range are considered as the objective functions. The NSGA-II multi-objective evolutionary optimization algorithm is utilized to demonstrate a set of possible answers in the form of the Pareto front.

391 Robust Design Optimization with Metamaterial by Additive Manufacturing

Klaus Hoschke, Marius Bierdel, Matthias Wickert

Additive Manufacturing and intelligent lightweight design through Structural Optimization are key technologies for the efficient use of resources and performance enhancement in product development. Structural Optimization chases for a more efficient design with respect to technical specifications and derived boundary conditions. Resulting potentially complex design solutions can then directly be manufactured by Additive Manufacturing. The geometrical freedom enabled by Additive Manufacturing allows for better design solutions by extending the design space and lowering restrictions. At the same time Structural Optimization is a chase of finding the structural limit of a design problem and its solution concept. Scratching on the structural limit, design solutions can lack robustness in regard to uncertainties. When with Additive Manufacturing the structural limit is approached, the preservation of robustness is crucial. On the other hand, the design freedom in Additive Manufacturing can actively be used to enhance robustness. An approach is presented that introduces Metamaterial in intermediate load carrying areas of a structural component under load uncertainties. Structural members and coherent mechanical characteristics of the hybrid structure account for the uncertainties of load application. Implementation of the approach is demonstrated in the product development of a structural aircraft component which is produced from aluminum with Additive Manufacturing.

392 Structural Optimization For Piezoelectric Acoustic Devices

Gil Ho Yoon, Hyung Gyu Choi, Jung Sik Choi

The application of piezoelectric materials presents many advantages such as reducing the number of parts of the system and its manufacturing cost. However, the performance prediction and the optimal design of piezoelectric material based devices are difficult because of the mutual couplings between piezoelectric and mechanics. Particularly, it becomes more difficult when acoustic system should be coupled with piezoelectric material based deices. Thus to obtain optimal performances, many optimization techniques have been developed. In the present study, after the development of the finite element procedure for vibro-acoustic performance, the TO method is incorporated and several optimal layouts of piezoelectric rings are found out to focus acoustic energy. In order to consider the manufacturing constraints, the modified morphology density filters are also developed.

393 GPU-Based Topology Optimization for Thermoelastic Problems

Stefan Gavranovic, Dirk Hartmann, Utz Wever

Additive Manufacturing revolutionized the way engineers create new designs. It gave an opportunity to explore much larger design spaces, therefore reducing design weight and increasing its performance. Topology Optimization [1] as a tool helps to obtain such optimal designs even for non expert users.

In order to have nearly interactive Topology Optimization tool, we implemented efficient geometric multigrid method [2] on structured hexahedral meshes using GPU. By means of a weak form enforcement of boundary conditions via Nitsches method [3] accuracies as required by engineering applications are achieved although adopting a non-conformal mesh approach.

Additionally, due to the nature of Additive Manufacturing process, we consider influence of thermal loads [4] in the optimization process. User experience is enhanced by integrating our tool within CAD system, thus simplifying preparation stage for a simulation.

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394 Definition of reference test cases for stress constrained topology optimization

Pierre Duysinx, Maxime Collet, Erin Kuci, Dirk Munro, Albert Groenwold, Matteo Bruggi

While topology optimization has mostly been based on compliance type formulations, industrial applications call for more elaborated design formulation including local stress constraints. Topology optimization with stress constraints initially considered in Duysinx & Bendsoe (1998) has taken benefit of several extensions, e.g. to consider non equal stress limits (Bruggi & Duysinx, 2013), global stress constraints (Duysinx & Sigmund, 1998), fatigue resistance (Collet et al. 2016) or Simultaneous Analysis and Design (SAND) Approach (Munro & Groenwold, 2016). Currently the topic is the subject of a growing number of research works. However a careful literature review reveals that the different works use multiple variants of the classical benchmarks such as the L-shape domain. Therefore it is difficult to establish a fair comparison of the performance of the proposed formulations. This point becomes really an issue since we are now facing the challenging question of finding efficient numerical procedures to reduce the computational load related to these very large scale problem solution.

Thus it comes that it is urgent to define reference benchmarks with clear geometrical and material data, boundary conditions and loadings. Based on our research expertise, we propose to define a set of reference test cases which will serve to assess the real performance of the novel contributions.

Besides the many single load case problems, it is necessary to propose new benchmarks that put forward the specific character of the stress constrained designs. Indeed, it has been demonstrated that they may differ from strength designs whenever there are different behaviours in tension and compression, several materials, or geometrical constraints. Beyond the famous three-bar truss problem, we are also to draw new reference benchmarks under these conditions.

Finally reference solutions will be presented for the proposed benchmarks to provide a first set of reference performance values.

397 Level-Set Topology Optimization of Large Deformation Dynamic Contact Problems

Kurt Maute, Matthew Lawry

This paper presents a method for the optimization of multi-component structures comprised of two and three materials considering time-varying, sliding and cohesive contact in the presence of large deformations. The structural geometry is defined by an explicit level set method, which allows for both shape and topology changes. The mechanical model assumes finite strains, a nonlinear elastic material behavior, and a transient response. Identification of overlapping surface position is handled by a coupled parametric representation of contact surfaces. A stabilized Lagrange method and an active set strategy are used to model frictionless and cohesive contact and separation. The mechanical model is discretized by the extended finite element method which maintains a clear definition of geometry. Face-oriented ghost penalization improves the stability of the physical response prediction. The structural response is advanced in time by an adaptive time-stepping algorithm. A nonlinear programming scheme is used to solve the optimization problem, which is regularized by introducing a perimeter penalty into the objective function. Sensitivities are determined by the adjoint method. The main characteristics of the proposed method are studied by numerical examples in two dimensions. The numerical results demonstrate improved design performance when compared to models optimized with a small strain assumption. Additionally, examples with load path dependent objectives display non-intuitive designs.

398 Material interpolation schemes in topology optimization problems involving coupled structural and thermal optimization.

Gieljan Vantyghem, Veerle Boel, Marijke Steeman, Wouter De Corte

Two widely used strategies for solving topology optimization problems are the density method and the homogenization method. In these methods, design problems are made continuous by letting the material density take any value between zero and one. In the FE discretization these densities are often approximated to be constant over each element and constitute the variables of the design problem. A relation is established between the element density and its material properties. This formulation, in the form of an interpolation scheme, has no simple physical meaning. In two dimensions, element densities can be interpreted as a varying thickness of the element, or as a porous micro-structure. In traditional topology optimization (considering one discipline) one can often choose to ignore the physical interpretation of the intermediate densities when the optimization results lead to black-and-white topologies anyway. On the contrary, when two or more physical phenomena are involved, for example when structural and thermal optimization processes are combined, intermediate densities can constitute part of the optimal solution. In this paper, we study a variety of distinct material interpolation schemes are their influence on the optimized topology for problems involving coupled structural and thermal analysis. The physical interpretation of these schemes is discussed and the effective properties of the intermediate densities are analyzed.

399 Design of cellular materials and meso-structures with improved structural and thermal performances.

Gieljan Vantyghem, Marijke Steeman, Wouter De Corte, Veerle Boel

Honeycomb structures and other types of cellular material provide a range of properties that make them suitable for use in many industrial applications. Some have great structural performances, other are good at dissipating heat. In topology optimization, a physical representation of intermediate densities is realized by interpreting them as porous micro-structures. Considering topology optimization in multi-physics, these intermediate densities can become part of the optimal solution. Scaling up those micro-structures into a meso-scale could inspire new material design. Advances in additive manufacturing methods capable of producing these cellular structures also add to the motivation. In this paper, the application of cellular materials for industrial applications in the building sector is demonstrated and FEM analysis is used to examine several types of meso-structures. In this study we focus on optimizing the relative density of these structures relative to their equivalent thermal conductivity and the effective E-modulus. Special attention is given to 3D situations for which the required properties are not necessary the same in all directions.

400 Optimal design of skeletal structures exhibiting nonlinear response

Hazem Madah, Oded Amir

In this work, we present a unified approach for optimization of skeletal structures (i.e. trusses and frames) that accounts for both material and geometrical nonlinearities. While the vast majority of studies in structural optimization rely on linear-elastic modeling, the proposed procedure provides freedom to the user to apply various kinematic assumptions, i.e. large deformations, large strains and rigid body motions, and to consider various constitutive relations, such as hyper-elastic or elasto-plastic. One family of applications is design problems with buckling and stress constraints, where instead of imposing a large number of constraints, we employ nonlinear models and drive the design by optimization towards a linear (or close to linear) response. Another class of applications is design synthesis involving large deformations, as encountered for example in MEMS.

In the proposed approach, the truss/frame members are modeled with geometric and material nonlinearities using a co-rotational beam formulation. Currently, material is assumed to be hyper-elastic whereas ongoing work includes elasto-plastic material laws. Design variables are either cross-section properties so that both topology and sizes can be optimized, or node coordinates so that shape optimization can be pursued. Sensitivity analysis follows the adjoint method and optimization is solved using well-established first-order methods.

In truss optimization problems for example, we show that the procedure leads to a buckling-resistant and stress-constrained design by maximizing the sustained load for a given prescribed displacement. When applying various imperfections, buckling of single members, unstable configurations and global buckling are all taken into account implicitly. Furthermore, optimizing for several levels of global deflections exposes the potential of the formulation in synthesizing highly nonlinear responses. Further applications and computational challenges will be discussed in detail.

401 Topology optimization method for variable-axial composite

Tsuyoshi Nomura, Atsushi Kawamoto, Tsuguo Kondoh, Axel Spickenheuer, Mario Petrovic, Shinji Nishiwaki

In this paper, a topology optimization method for variable-axial composite is presented. The variable-axial composite is a class of fiber reinforced composites which consists of inhomogeneous distribution of fiber axis. There are several technologies to realize such composites, such as tow placement system, automatic tape laying system, tailored fiber placement system, continuous fiber printing technologies and so on. Especially, the tailored fiber placement system, TFP, and the continuous fiber printing system offer great flexibility of fabrication of variable-axial composites in 2D. In addition to that, with TFP system, the structures can be afterwards even draped in 3D shapes. Virtually, designers can layout fiber orientation almost freely with these systems. However, there are no design methodologies which are capable to exploit maximum performance by utilizing such flexibility. Topology optimization method can be considered as the best framework to build on such a design method not only because it is the most flexible structural optimization method but also by the fact that the method can handle anisotropic materials orientation distribution naturally because the topology optimization was originally proposed as the homogenization design method which assumes the presence of anisotropy induced by orientation of microstructure of the material. In this presentation the idea of free orientation layout design is revised and re-implemented with explicit vectorial orientation design variable field. The method offers continuously varying orientation distribution design which is concurrently optimized with density field to realize simultaneous design of topology and orientation distribution.

402 Predicting B-Basis Allowable at Untested Points from Experiments and Simulations of Plates with Holes

Yiming Zhang, Jaco Schutte, John Meeker, Upul Palliyaguru, Nam Kim, Raphael Haftka

B-basis allowable is widely used as conservative estimate of composite strength. Various methods for calculating B-basis allowable by repeating tests for a fixed structural configuration are well documented. However, predicting the allowable at untested points is less well explored. The proposed paper will explore the options of predicting B-basis allowable using the surrogate that is built on using experiments and simulations. We firstly explore the following options: (i) fitting only experiments in parameter space; (ii) correction approach to combine simulations with experiments using multi-fidelity surrogates; and (iii) calibration approach using experiments to calibrate physical parameters in a failure criterion. For the abovementioned options, we consider two possible flavors. The first is to use all replicates in the experiments to develop surrogates for mean values and scatter. This implementation has been derived strictly for independent and identically distributed (i.i.d.) random variables. The second approach is to calculate the B-basis at each test point by existing single-point estimation and use only this data to develop surrogates. Different single-point estimation schemes of B-basis allowable could be adopted based on distributions. The second approach may be more robust for replicates beyond i.i.d. random variable. We have performed the Open-Hole-Tension tests following ASTM standard to evaluate the different options. Surrogates are constructed using data generated from tests of composite plates with holes with two design parameters: the size of the hole and the percentage of 45-degree plies in the laminates. We have resampled subsets of experimental data to account for the effect of experimental variability. There are two major observations: (1) Fitting experiments alone is preferable except when very few experiments are available. (2) Combining single-point estimation with surrogates allows for desirable conservative estimation.

403 Multi-scale Docking Method in Computer-aided Molecular Design

Ling Kang, Hong Wang, Junfeng Gu

Development of computer science has greatly enhanced both speed and accuracy of the computation and data analysis, and promoted the research of drug molecular design methods and applications. Novel theories and approaches have become a major avenue for drug discovery efforts at the postgenomicera. Molecular docking, as a main method of computer-aided drug design, has been successfully used in the drug discovery process.

This paper is to study multi-scale method in the molecular docking. Based on the previous studies, the authors introduced the residue groups and key residues into the description of protein structure model: the protein molecule would be divided into several groups, and .the motions for each group would reflect the movement of the receptor; the partial flexibility of the receptor would be described by the sidechain dihedral angles of the key residues. During the process of molecular combination, there are concerned many interactions such as Van der Waals interaction, electrostatic interaction, hydrogen bonding, solvent effect, and the entropy etc. All these factors are combined to affect the protein and the ligand, and ultimately form a stable complex conformation, which is a conformation with the lowest binding free energy.

Based on some early studies, the authors developed a new evaluation mechanism. As for the optimization algorithm, based on the former evolvement-based genetic algorithm, more strategies are considered to speed up the optimizing process and ensure rapid and steady convergence.
Combined with the aforementioned molecular flexibility description and score functions, the authors built a multi-scale optimization model for molecular docking. New molecular docking software has been developed on the Drug Discovery Grid. The docking results show that the method can get reasonable grid speedup and efficiency.

404 Parameter Estimation Based on Model Reduction and Surrogate

Hong Wang, Ling Kang

The major goal of systems biology is the establishment of mathematical models describing cellular processes at a molecular level. Constructing mathematical model is comprised of writing kinetic rate equations that describe the time rate of change of various chemical species and determining the unknown parameters in those equations. For most biological models, parameters cannot be determined directly in specific experiments but instead to be estimated from systems-wide data. The task of determining parameters from data often is finished by optimization algorithms. However, sloppiness of the model restricts effects of many optimization algorithms for parameter estimation and presents huge computational challenges. In this paper, a model reduction method based on sloppiness are used as surrogates for the full forward model. Then stiff parameter combinations, which strongly decide behavior of the model, are identified by optimization algorithm. Finally, a numerical examples illustrate the efficiency of the proposed approach.

405 Optimum channel design of a redox flow battery via topology optimization

Kentaro Yaji, Shintaro Yamasaki, Shoji Tsushima, Takahiro Suzuki, Kikuo Fujita

In this study, we present a novel framework of optimum design method for the flow field in a vanadium redox flow battery (VRFB), which is a promising next-generation storage system for renewable energies such as wind and solar power. In recent VRFB systems, not only thin carbon fiber electrodes but also flow channels are exploited, in order to boost the charging/discharging performance, whereas only thick carbon fiber electrodes are used in conventional VRFB systems. It is widely known that the flow channel geometry greatly affects the battery performance, and thus explorations of an ideal flow field have been attracted a great attention in the research field of VRFB. Several researchers investigated the effects of the battery performance on various patterns of flow channel by experimental and numerical approaches. The ideal flow field is, however, obviously dependent on VRFB systems, and only geometrically simple patterns, e.g., serpentine, parallel, and interdigitated flow fields, were dealt in the previous works. Since an optimum pattern of the flow field is not obvious and the flow channel is a significant component for improving the performance, topology optimization is a promising methodology for the design of high-performance VRFBs. To explore innovative designs of VRFBs, we construct an optimum design method for the flow field in a VRFB, on the basis of topology optimization. The optimization problem is formulated as a maximization problem of a charging efficiency, in which the electrochemical reaction and the electrolyte flow are considered. In this presentation, we discuss the efficacy of the proposed method for the design of VRFBs.

406 Topology Optimization of Power Semiconductor Devices

Katsuya Nomura, Tsuguo Kondoh, Tsuyoshi Ishikawa, Shintaro Yamasaki, Kentaro Yaji, Kikuo Fujita

In this paper, topology optimization is applied to the design of power semiconductor devices. The doping density distribution of power semiconductor devices is optimized using a density-based topology optimization method. The density method is suitable for the design of power semiconductor devices because doping density can take on continuous values and is intrinsically free from the gray-scale problem. The governing equation of power semiconductor devices is the drift-diffusion model, which is a system of three simultaneous equations with dependent variables of electrostatic potential, electron density, and hole density.
To verify the effectiveness of topology optimization, optimization is conducted for two types of two-dimensional design problems. At first, optimization of a p-n diode is performed to improve the trade-off between the breakdown voltage and on-resistance. This is formulated as a single-objective optimization problem with the KreisselmeierSteinhauser (KS) objective function of the electric field, which indicates the breakdown voltage characteristics, under the constraint of the on-resistance. By optimization, a p-i-n diode, which is a well-known diode structure, is obtained and the trade-off is improved. Next, optimization of a junction termination structure is performed to improve the breakdown voltage characteristics with the consideration of the ion implantation, which is one of the fabrication processes used for power semiconductor devices, under the process variation. The optimized structure obtained is ensured to be manufacturable and more robust to the dose amount variation of ion implantation than the initial structure. These results demonstrate the effectiveness of topology optimization for the design of power semiconductor devices.

408 Optimum Design on Neck Embossing Decoration of Aluminum Beverage Bottles

Jing Han, Koetsu Yamazaki, Akiyoshi Matsuzaki

Over the last ten years, the consumption of a two-piece aluminum beverage bottle of a wide neck increases year by year because of its re-sealability as well as other advantages of metal beverage packaging. Moreover, neck decoration by means of metal printing and embossing, can display more information and can catch more easily consumers attention. There are two kinds of conventional embossing methods for bottles. The first one is rotary embossing. This method can be applied for various embossing patterns, but it is not available for neck embossing because the internal die cannot be inserted into the bottle after a necking process. The second one is linear embossing. This method can be efficiently applied to emboss the bottle neck, but only for relatively simple patterns.
This paper proposes a new forming method to emboss the aluminum bottle neck with various relatively fine embossing patterns. In the proposed method, instead of the internal die and internal pressure, a directional distributed load is applied only to the inner surface of the

neck, against an embossing die placed outside of the neck. An in-house software is developed to build efficiently finite element analysis models, based on embossing pattern images, to simulate neck embossing process proposed. The numerical simulations are then performed to investigate influences of the die fillet radius, the distributed load and embossing pattern on the neck embossing results, such as the thickness reduction and the outlook of the embossed region. An optimum design flowchart is also proposed to design neck embossing, and a structural optimization method is applied to obtain an optimum solution. The optimum design result shows that, by optimizing the die fillet radius and the distributed load, subject to the maximum thickness reduction ratio and the range of outlook assess factor of the embossed region, the optimum embossed neck can be obtained under consideration of vision, touch and surface coating protection.

409 A randomized approach based on stochastic sampling for topology optimization with many right-hand sides

Xiaojia (Shelly) Zhang, Eric de Sturler, Glaucio Paulino

We propose an efficient probabilistic method to solve a deterministic problem – we present a randomized optimization approach that drastically reduces the enormous computational cost of optimizing designs under many load cases for both continuum and truss topology optimization. Practical structural designs by topology optimization typically involve many load cases, possibly hundreds or more. The optimal design minimizes a, possibly weighted, average of the compliance under each load case (or some other objective). This means that in each optimization step a large finite element problem must be solved for each load case, leading to an enormous computational effort. On the contrary, the proposed randomized optimization method with stochastic sampling requires the solution of only a few (e.g., 5 or 6) finite element problems (large linear systems) per optimization step. Based on simulated annealing, we introduce a damping scheme for the randomized approach. Through numerical examples in two and three dimensions, we demonstrate that the stochastic algorithm drastically reduces computational cost to obtain similar final topologies and results (e.g., compliance) compared with the standard algorithms. The results indicate that the damping scheme is effective and leads to rapid convergence of the proposed algorithm.

410 An Asymptotic Approach for Nonlinear Topology Optimization Considering Plasticity with the Drucker – Prager Model

Tuo Zhao, Adeildo Ramos Jr., Eduardo Lages, Glaucio Paulino

We address nonlinear topology optimization problems considering plastic material behavior by means of mathematical asymptotic analysis using a fictitious nonlinear elastic model. The material nonlinear model is governed by the Drucker Prager yield criterion. From an algorithmic viewpoint, we consider the topology optimization problem subjected to prescribed energy, which leads to robust convergence in nonlinear problems. The objective function of the optimization problem consists of maximizing the strain energy of the system in equilibrium subjected to a volume constraint. The sensitivity analysis is quite elegant in the sense that there is no extra adjoint equation. In addition, the nonlinear structural equilibrium problem is solved by means of direct minimization of the potential energy using Newtons method with a backtracking line search strategy. To illustrate the features of the implementation, we present numerical examples displaying convergent results for optimal structures in the plastic range using either quadrilateral or polygonal elements.

411 Reliability Based Design Optimization of The Gap Size of Annular Nuclear Fuels in Pressurized Water Reactor (PWR)

Jaehyeok Doh, Jongsoo Lee

Annular fuels used in the pressurized water reactor (PWR) have wider surfaces than conventional solid fuels, which promote better heat transfer by the heat generation. The surface temperature of annular nuclear fuels can be reduced compared to conventional solid fuels, which means there is some extra margin to the unexpected transient situations. Thermal-elastic-plastic-creep (TEPC) analysis was conducted using an in-house program on Visual FORTRAN that adopted the effective-stress-function (ESF) algorithm. In this study, design optimization of the gap size of annular fuels was conducted. For this, TEPC analysis of annular fuels was performed using in-house code to find the contacting tendency of the inner and outer gaps between the annular fuel pellets and cladding. The tensile, compressive hoop stress and temperature were also measured. Metamodel by the Kriging of objective and constraint functions were generated using calculated performance data under optimal latin hypercube design (OLHD). The accuracy of approximate models was evaluated through root mean square error (RMSE). Using these models, the gap size of PWR annular fuels were deterministically optimized using the micro genetic algorithm (MGA) for increasing heat transfer efficiency and generation of lower level stress. For considering uncertainty and satisfying reliability, The obtained optimal solutions by MGA were set as the initial value conducting reliability based design optimization (RBDO) . Optimal gap size was validated through the TEPC analysis of PWR annular fuels and compared with the obtained optimum solutions according to optimization method as MGA and RBDO. One can see that optimum solutions are conservative considering uncertainties.

412 Conductor layout optimization for reducing the magnetic coupling noise of a filter circuit board

Hiroki Bo, Shintaro Yamasaki, Kentaro Yaji, Katsuya Nomura, Atsuhiro Takahashi, Kikuo Fujita

The aim of this research is to reduce the amount of high frequency noise propagating through space in a low-pass filter. Generally, high frequency noise is generated from power electronics equipment that is responsible for converting direct current and alternating current in hybrid cars. A device consisting of capacitors and inductors called the low-pass filter is used for absorbing the high frequency noise. Ideally, the low-pass filter absorbs more noise as its frequency is higher, but in practice, the noise absorption rate decreases beyond a certain frequency. This is because of the following reasons. The magnetic flux is generated from a current loop in the circuit according to Ampere's circuital law. Then, this magnetic flux causes high frequency noise at the output terminal according to Faraday's law of induction. This phenomenon is called magnetic coupling. The amount of noise that appears at the output terminal depends on the layout of the conductor on the circuit board. Conventionally,

designers reduced the area of the current loop to avoid the influence of magnetic coupling. However, it was difficult for them to quantitatively predict the influence and design the conductor pattern optimally. In contrast, a topology optimization method is valid for obtaining a mathematically evident optimal structure. Topology optimization method usually allows grayscale area, which holds intermediate density value. For the conductor layout problem, it is difficult to appropriately set the current conductivity to the intermediate material density, and this possibly causes a computational error. For these reasons, we propose a grayscale-free topology optimization method for the conductor layout that minimize the influence of the magnetic coupling. Several numerical examples are provided to confirm that the appropriate optimal structures are obtained.

413 Multi-phase field topology optimization with multi-scale analysis for maximizing heat conductivity of a metallic material with crystalline structure

Junji Kato, Toshiba Ichibangase, Shun Ogawa, Tomohiro Takaki

The material design to obtain an optimal microstructure applying a numerical approach is receiving a lot of attention, especially in the field of advanced materials, such as special alloys and fiber reinforced polymers. However, the geometry of microstructure of alloys shows complex crystalline structure, which the conventional topology optimization is unsuitable to represent. For this reason, the present study challenges to develop topology optimization scheme for crystalline metals applying the Multi-Phase Field (MPF) method. The objective is to maximize the heat conductivity of a macrostructure consisting of dual-phase crystalline metal with respect to a prescribed material volume. In this context, multi-scale analysis must be considered to represent the hierarchical and mechanical relationships between different scales and these relationships also must be affected to the optimization algorithms.
This challenging work should be of great value in the field of material science and material design and its versatile framework is introduced. The proposed method is examined by a series of numerical examples and eventually verified that it can provide a reliable optimal design for crystalline metals to maximize the heat conductivity of macrostructures.

414 Enhanced PID Control Optimization of Hovering Quad-Copter for Robust Flight Stabilization

Jaehyun Yoon, Jongsoo Lee

In this study, the enhanced PID (PIDE) technique was applied to solve the problem of the D controller in the PID control technique of the quad-copter. The purpose of this study is to improve the control algorithms so that the mission can be performed in complex control commands for application to real quad-copter. The control algorithm was developed using Matlab SIMULINK. As unmanned becomes more important in the modern society, the unmanned air space is also being used. As a result, the role of the drone has become important and has been used in various fields. The quad-copter, which is the subject of this study, designed optimized quad-copter body shape and blade shape through previous studies. In order to control the posture of unstable quad-copter, the control amount was confirmed through PID control to reach the desired target value, and it was confirmed that there is defect in the D controller. The conventional D controller is a method of controlling the power applied to the motor by the difference between the target value and the measured value as an input signal. In this study, the input signal to the D controller is used to input the measured value, not the difference between the target value and the measured value. PIDE was able to confirm that the system does not become unstable even when the target value suddenly changes while performing the same role of the D controller.

415 Shape optimization for frictional contact problems using semi-analytical sensitivity analysis and its application to design of an aero-engine turbine component

Cao Niu, Weihong Zhang

This paper presents a shape optimization approach for linear elastic frictional contact problems in the node-to-node contact framework. Due to the path-dependent characteristic of friction, shape sensitivity formulation is derived via applying direct differentiation to the discretized equilibrium equations at the convergence of each load increment of the incremental iterative Newton-Raphson solution procedure and implemented by using a semi-analytical method in commercial finite element software ANSYS to take advantage of its robustness and multi-physics field processing capability. The zero normal nodal contact forces and their sensitivities are respectively modified into the values and sensitivities of corresponding normal contact gaps times an elaborately selected coefficient. This facilitates necessary effective control over normal contact pressures during optimization process. The validities of the sensitivity analysis procedure and the zero normal contact force modification strategy are verified by a Hertz contact problem between two cylinders with analytical solutions. Finally, the proposed approach is further demonstrated with an application to shape optimization design of an aero-engine low-pressure turbine component suffering from complex temperature field and high-speed revolution loads with consideration of leakproofness.

416 Quadratic Multipoint Exponential Approximation: Surrogate Model for Large-Scale Optimization

Robert Canfield

Sequential Linear Programming (SLP) is a well-known first-order optimization method. Sequential quadratic programming (SQP) is generally preferred for smooth problems, because it is second-order accurate; however, it suffers from the curse of dimensionality for large numbers of design variables. For large-scale problems, SLP may be a good alternative, although its performance depends on the move-limit strategy, the efficiency of the LP solver, and obviously the nonlinearity of the functions. A robust implementation of SLP with a trust region strategy is implemented here in conjunction with a large-scale LP solver. The number of SLP outer-loop iterations to converge is demonstrated to be reduced by an intermediate variable transformation during the linearization. The well-known two-point exponential approximation (TPEA) is extended to take advantage of more than two previous points in determining intervening variables, which can be beneficial particularly for temporarily inactive variables. A single set of intermediate variables are selected for use with all constraint

and objective functions, based on Lagrangian sensitivity, to maintain a linear sub-problem for SLP. Quadratic terms constructed in a reduced sub-space are explored for efficient large-scale SQP.

417 Parameterized level set-based topology optimization considering symmetry and pattern repetition constraints

Peng Wei, Zuyu Li

This paper presents a parameterized level set-based topology optimization method for continuum structures considering symmetry and pattern repetition constraints, which may contribute to practical engineering designs. In the proposed method, the design domain is split into a certain number of subdomains according to the constraints imposed. Here, the subdomains are assumed to have different geometries and irregular finite element meshes, which is different from many former researches concerning manufacturing constraints that use the level set-based method.

The level set functions implicitly describing structural interfaces of each subdomain are respectively interpolated by the Radial Basis Functions (RBFs) centered at the given sets of unstructured design points. Here, the idea of separating design variables and finite element meshes is employed. As the key technology, the symmetry and pattern repetition constraints are all imposed on the design points rather than the finite element nodes. And then the relationship between the level set value of finite element nodes and unstructured design points are naturally established according to the RBF interpolation.

Finally, various numerical examples for minimum mean compliance problems are provided to demonstrate the capability and effectiveness of the proposed topology optimization method.

418 Integrated design of permanent magnet synchronous motor by incorporating magnet layout and yoke topology optimizations

Shun Maruyama, Shintaro Yamasaki, Kentaro Yaji, Kikuo Fujita

Permanent magnet synchronous motor (PMSM) is an efficient high power motor. The PMSM consists of a stator and a rotor. The rotor consists of multiple permanent magnets (PM) and one yoke. Torque performance of the PMSM is improved by structural optimization of the PM layout and the yoke shape, because the performance mainly depends on them. It is complicated problem to optimize both of them, because the optimal PM layout and yoke shape cannot be obtained independently. When those two optimization problems are solved simultaneously, it is difficult to find the optimal solution due to large feasible region.
Therefore, in this research, we divide the original design problem into sub problems, and these sub problems are integrated with the following procedure.
First, we obtain optimized yoke shapes for several given PM layouts by using topology optimization. Second, we construct a response surface of the PM layout parameter using the solutions of the first problem, and find an optimal PM layout. Finally, we obtain the optimized yoke shape for the optimal PM layout.

The proposed method solves a combined optimization problem including sub problems that are difficult to solve simultaneously but depend mutually.
The usefulness of this method is discussed with numerical examples.

419 An Adaptive Continuation Method for Structural Topology Optimization Considering Buckling Constraints

Xingjun Gao, Haitao Ma

Structural strength, stiffness, and stability are three of the most important factors which should be considered for assessing structural designs. Therefore, in order to achieve safe and practical designs, structural stability must be taken into account during a structural optimization procedure. Buckling optimization has drawn more research attention in recent years.

Some issues in the topology optimization of continuum structures considering structural stability are investigated. The optimization problem of compliance minimization under constraints on material volume and buckling load factors is considered. The Solid Isotropic Material with Penalization (SIMP) material model is used for topology optimization and a hybrid stress element is employed in structural analysis.

The authors have recently found that, there is often a conflict between requirements for structural stiffness and stability when the amount of material is fixed, and because that this conflict is usually overlooked, conventional optimization algorithms may either suffer from slow convergence or even fail to produce desired designs. While the continuation method is effective for conventional compliance minimization problem, it is found that, for the optimization problem considered in the study, the direct use of this method is not very successful either. An adaptive continuation method is proposed, in which the penalty parameter is automatically adjusted during the optimization procedure according developed rules. Using these rules, buckling constraints would be properly considered throughout the optimization to guide optimized designs to move in more appropriate directions.

Numerical examples will be presented to demonstrate the effectiveness of the proposed method and future applications of the method discussed.

420 A gradient-based topology optimisation for radar cross sections in two-dimensional acoustics

Hiroshi Isakari, Toru Takahashi, Toshiro Matsumoto

Radar cross section (RCS) is a measure of target object to reflect wave signals in the direction of wave receiver. The RCS is often used in electro-magnetics, however, the concept can straightforwardly be extended in acoustics to evaluate the sound performance of sound object. By manipulating the RCS of sound objects, we can design sophisticated sound devices.

In this study, to design a sound device which has a desired RCS patterns, we propose a gradient-based topology optimisation. The related topological derivative, which characterises the sensitivity of the RCS in a pre-fixed direction to an appearance of an infinitesimal circular object, is rigorously derived. We show that the topological derivative consists of two terms, one of which is evaluated by the adjoint variable method and the other with a direct calculation. We emphasise that the second term has a significant influence on the performance of the optimisation.

Furthermore, the derived topological derivative is implemented in a topology optimisation. We use the level set method to express sound objects and the boundary element method to solve the relevant acoustic problems in the process of the optimisation. These choices are reasonable since the RCS is, with the help of reciprocal theorem, evaluated as (a square of) a boundary integral. It is important to express the boundary of sound objects and evaluate the boundary integral in an accurate manner.

In the oral presentation, we show several numerical examples of optimal designs for acoustic objects with desired RCS patterns.

422 Stress-constrained topology optimization with multiple discretized densities and superconvergent patch recovery.

Seongyeol Goo, Semyung Wang

In stress-constrained topology optimization using qp-relaxation method, a discrete 0/1 solutions are preferable to assure physical consistency. However, eliminating gray elements using filtering technique produce artificial stress concentrations near boundaries. Hence, element stresses near boundaries are not accurate, and more materials are needed to compensate theses stress concentrations. To resolve this problem, we proposed a novel topology optimization framework that does not suffer from artificial stress concentrations. In this method, a single finite element has multiple densities and numerical integrations are performed at the center of these densities. In this way, displacements near the boundaries are more accurate than those obtained from conventional discretization (one density per element). With these improved displacements, nodal stresses are computed using superconvergent patch recovery. Then, stress at each density is interpolated using recovered nodal stress and shape functions. Numerical examples are presented to validate the proposed method. The optimization results show that the optimized structure does not suffer from artificial stress concentrations, and the stress distributions show a good agreement with those obtained from the post-processed finite element models.

423 Response-weighted maximin distance design for multi-sampling

Cho Su-gil, Park Sanghyun, Jang Junyong, Lee Minuk, Min CheonHong, Lee Tae Hee

In a computational experiment, space filling designs that fill design space uniformly on the overall design domain are widely used for making matamodel more accurately and perform optimization more efficiently. However, the methods have a disadvantage that extracts unnecessary points in terms of an optimization because it considers only the input information. To resolve the disadvantage, sequential approximation optimization (SAO) methods have developed. The methods adopt the prediction value of metamodel to a criterion for the next sample point. However, the SAO methods have several critical drawbacks hard to employ complex engineering applications. Firstly, a question is how to guarantee the accuracy of metamodel which is iteratively updated in the optimization process. Sample points of SAO from inaccurate metamodel may be unnecessary points. Secondly, the SAO methods are unappropriated to perform multi-sampling. Because the parallel processing has receive much attention to relieve computational burden in optimization, multi-sampling is one of important measure to evaluate computational exp[eriment method. For these reasons, new sequential sampling strategy is required. In this paper, a sequential design of experiment method, which uses only real responses without metamodel in the sampling stage, is proposed. It also is able to select the multi-samples because the method is based on maximin distance sampling with space-filling concept. Compared with original maximin distance sampling, the proposed method can place more samples in neighborhood of the designer's target region, e.g., minimum or maximum. Proposed method employs weighted distance concept that can consider responses with the basic statistical information of sample points, e.g., probability density function (PDF) or cumulative density function (CDF), while satisfying the space filling design.

426 A topology optimisation of wave absorbers in two-dimentional electro-magnetic field with an accelerated BEM by the H-matrix method

Kenta Nakamoto, Hiroshi Isakari, Toru Takahashi, Toshiro Matsumoto

Wave absorber is a device which absorbs the electro-magnetic wave in a certain range of frequency. Wave absorber can be used to improve the performance of electro-magnetic devices by suppressing the electro-magnetic interference between some devices.

In this study, we consider to design wave absorbers by a topology optimisation. We define an objective function as the amount of time-averaged Poynting vector on boundary of a design object, and consider to maximise the objective function. The sensitivity of the objective function is rigorously derived as a variation of the objective function when an infinitesimal dielectric element is created in the design domain by using the adjoint variable method. In the case that objective function is defined on the boundary, rigorous evaluation of the electro-magnetic response on the boundary is essential. For this purpose, we employ the boundary element method. In the boundary element method, radiation condition is automatically satisfied with the help of the Green function, which enables us to treat problems defined in the infinite domain strictly. Furthermore, by using the accelerated LU decomposition with the H-matrix method to solve the algebraic equations derived by the BEM, we achieve the fast computation of the sensitivity. We efficiently compute the optimal configuration of wave absorbers by applying the sensitivity analysis to a level-set-based topology optimisation.

In the oral presentation, we show some numerical examples which show the efficiency of the sensitivity analysis and effectiveness of the topology optimisation algorithm.

427 On large-scale singular solutions in local stress-constrained topology design

Dirk Munro, Albert Groenwold

We present novel results obtained in the 'simultaneous analysis and design' (SAND) or 'direct' setting of the density-based local stress-constrained topology optimization problem. The solution method is a standard gradient-based sequential approximate optimization (SA0) technique: the quadratic approximate subproblems are strictly convex and separable, the subproblems are calculated with primal-dual interior-point quadratic programming routines, and, in order to enforce convergence and termination, the steps are restricted with an adaptive trust-region technique.

It is demonstrated that material density variables are allowed take on a value of zero exactly on the lower bound—indeed, the form of stress constraint considered is termed a 'vanishing constraint'—this permits the stresses in regions of void material to take on any value, which, in turn, circumvents the infamous stress singularity problem. Moreover, in SAND the typically expensive sensitivity analysis associated with state-based constraints reduces to the calculation of simple and sparse partial derivatives, hence, solutions to large scale problem instances may be obtained in a reasonable amount of computation time.

428 Knowledge discovery in dataset generated by topology optimization

Shintaro Yamasaki, Kentaro Yaji, Kikuo Fujita

In this presentation, we propose a new approach to obtain design knowledges of superior structures using dataset generated by topology optimization. The basic idea of this approach is incorporating Knowledge Discovery in Databases (KDD) and topology optimization. That is, we construct a database that records various material distributions generated by topology optimization for various structural design problems, including the varieties of design domain shapes, boundary conditions, and performance indicator functions, and then, we find appropriate material distributions in the database for a given design domain, boundary condition, and performance indicator functions. Furthermore, the proposed approach is designed such that we can easily change the performance indicator functions used to evaluate material distributions. By doing so, we can easily test various indicator functions and obtain knowledges for appropriate setting of indicator functions, i.e., formulation. Here, we emphasize that optimization itself is not performed in the proposed approach (preparing various material distributions is the precondition). For achieving success, it is important to carefully construct a framework for dealing with numerous data records and finding appropriate material distributions among them. In contrast to conventional topology optimization methods which find optimized material distributions under given formulations, the proposed approach aims to find appropriate formulations for structural design problems. Furthermore, it is expected that beneficial design knowledges, e.g., features of superior structures will be found by the proposed approach. We present a simple prototype system based on the proposed approach and discuss the potential of the proposed approach.

430 Topology Optimization with Super-Elliptical Discrete Object Projections

Seung-Hyun Ha

In this research, topology optimization method is applied for material design problems with discrete object inclusions such as composite materials. For these materials, the shape of discrete object is prescribed with Super-elliptical parameterization, which results in various inclusion shapes such as circles, ellipses, super-rectangles, and even astroids. Based on the conventional topology optimization method with design sensitivity analysis, Heaviside Projection Method is applied according to the shape of inclusions. Each active design variable projects solid-phase material with the prescribed Super-elliptical shape onto the design domain, which is surrounded by void-phase material, and this prevents overlaps from adjacent discrete objects. Through various numerical examples, it is clearly shown that various shapes and sizes of discrete objects are introduced by simply changing parameters for the Super-ellipses, and the number and position of discrete objects are naturally determined during the optimization. Also, this approach enables precise control on the length scale of discrete objects, and it helps to understand the nature of some engineered materials composed of non-overlapping discrete objects such as fiber or particle-reinforced composite materials.

431 Topology optimization with stress constraints using isotropic damage with strain softening

Yakov Zelickman, Oded Amir

Considering stress constraints in continuum topology optimization is challenging because the optimization involves a large number of design variables as well as a large number of constraints. The most common approach is to aggregate the constraints into a single or a few global approximate functions. A different approach was proposed recently in which an elasto-plastic response is considered and plastic strains are minimized, so that the yield conditions can be enforced implicitly (Amir, 2016). The main drawback of this approach is the added computational cost due to the nonlinear analysis. In the current work, we aim to reduce the computational burden by using a simpler, yet effective, nonlinear material law.
In the proposed approach, the continuum domain is modeled with isotropic damage and strain softening. The optimization problem involves only compliance and volume that can play the roles of either the objective or the constraint. An attractive aspect of this formulation in that no actual stress constraint is necessary. Once strain softening is considered, material that is strained beyond the yield strain becomes uneconomical in terms of strength. Therefore, the design is driven towards the utilization of material up to the yield strain and not beyond it meaning that the stress constraint is imposed implicitly by the model.
Preliminary numerical experiments show promising results: the proposed procedure is capable of generating stress-constrained topological layouts that match results achieved by various other approaches. For reducing the computational effort of nonlinear analysis and of the corresponding adjoint sensitivity analysis, we investigate also a path-independent nonlinear response, leading essentially to a strain-softening nonlinear elastic law. Finally, we discuss the relations of the current work to previous studies based on inelastic damage (James and Waisman, 2014), elastic damage (Verbart et al., 2016) and elasto-plasticity (Amir, 2016).

432 Simultaneous shape and topology optimization of prestressed concrete beams

Emad Shakour, Oded Amir

Even though topology optimization is a promising digital design approach, it had so far little impact on traditional structural engineering as practiced in the construction industry. This is despite the need to reduce consumption of construction materials, particularly concrete, due to their negative environmental impact. At the same time, prestressing can lead to a more effective utilization of concrete properties. In this work, we combine density-based topology optimization with the shape optimization of prestressing cables. This leads to a unified approach for optimal design of prestressed concrete beams.

In the proposed approach, concrete is modeled as an elastic 2-D continuum based on the common practice of designing prestressed concrete in the strictly elastic regime. The cable is modeled using piece-wise linear segments that are embedded into the continuum according to their geometric locations and the hosting shape functions. The forces in the cable are transferred as equivalent point loads. Design variables are assigned to the densities of each continuum point and to the vertical coordinates of the cable. This leads to a concurrent shape and topology formulation that is solved using sequential convex programming, based on adjoint sensitivity analysis. A special filtering and projection technique is tailored in order to enforce the existence of concrete cover around the prestressing cable.

The computational procedure is first verified by optimizing the cable shape only, leading to profiles that resemble design practices of post-tensioned monolithic beams. Then we present several examples of simultaneous shape and topology optimization. Unique layouts are found that cannot be achieved by separating the problem into two phases of sequential shape and topology or vice-versa. Finally, we discuss several potential extensions, for example the consideration of quasi-brittle behavior of concrete and the treatment of the prestressing force as a design variable.

434 Contributions to handle maximum size constraints in density-based topology optimization

Eduardo Fernández Sanchez, Maxime Collet, Simon Bauduin, Etienne Lemaire, Pierre Duysinx

The maximum size control in topology optimization can be required because of technological limitations, cost or even for aesthetic reasons. It could be the tool for designers to account for desired properties that are difficult to impose in the optimization problem. For example, to reduce bulky-printed parts in additive manufacturing and avoid the overheating problem, or for improving performance of structures under local damage by diversification of the load path.

A robust formulation for defining maximum size in density-based topology optimization relies on local constraints. It restricts the amount of material in the neighborhood of each point in the design domain (Guest, 2009). Due to the large number of constraints, a big computation time is required by the optimizer. This problem hinders the possibility of solving industrial problems.

We present two developments for reducing the computation time. The first one affects the constraints formulation by agglomerating them using the p-mean and p-norm, classically used for stress constraints. The second one is a modification of the maximum size domain, where a ring-shape is considered instead of a circle around the element. This modification reduces the size of the neighborhood and thus the computation burden. It has an impact on the final topology achieving better optimal values than a circular domain. In addition, another interpretation of the involved parameters allows for the definition of the minimum gap between solid members, increasing the designer's control over the geometry.

The proposed developments are tested with SIMP compliance minimization of 2D-domains showing good results in terms of time and optimized solution.

435 Optimum Designs for Plate-Like Aircraft Wings under Flutter Constraints

Scott Townsend, Renato Picelli, H. Alicia Kim

A coupling between unsteady aerodynamics and structural vibration gives rise to the flutter phenomenon: steady or growing oscillations leading to catastrophic structural failure. Minimum-weight aircraft wing design, with an emphasis on avoiding flutter, has been studied since the 1960's. The majority of works to date were posed as sizing problems; only a handful of researchers have employed a topology optimization approach.

The aim of this study is to utilise SIMP topology optimization to identify the structural features which increase the flutter resistance of aircraft wings in a least-weight sense. We have, so far, produced results for rectangular wings at a range of sweep configurations, all of which demonstrate the ability to significantly reduce wing weight while maintaining the flutter speed above a specified value, which in many cases can be even higher than that of a homogenous design. For example, we have demonstrated for a rectangular aspect-ratio 6 wing a weight reduction of 27% with simultaneous flutter speed increase of 25%.

We include several planforms studied previously in order to validate the obtained results: Ours are comparable, and include several new features not previously-identified, which are analyzed further and will be discussed in the full presentation. Furthermore, we include a number of planforms with unique stability characteristics not previously studied via topology optimization, i.e. delta and high aspect ratio wings. We submit that the research to be presented can provide insights into optimum aeroelastic wings, particularly useful for developing unconventional aircraft configurations.

436 Surrogate-based Aerodynamics for Composite Wing Box Sizing

Marco Tito Bordogna, Dimitri Betteghor, Christophe Blondeau, Roeland De Breuker

The objective of the paper is to develop an aeroelastic optimization framework capable of performing structural sizing considering structural and aerodynamic responses. The framework is created around the commercial FE tool MSC.NASTRAN, whose solver 144 is capable of computing aeroelastic loads using the Doublet Lattice Method (DLM). However, aerodynamic performance cannot be properly constrained due to the limitations of panel methods.

The proposed framework utilizes a surrogate model based on rigid CFD RANS computations and provides the optimizer with a high-fidelity lift and total drag estimation that includes all drag components and not only induced drag. The input of the surrogate model are the wing displacement and the wing angle of attack. A shell elements FE model of a composite wing is used to obtain realistic weight estimation and structural responses. The wing structure displacement, which is used by the surrogate model, is approximated with a projection-based reduced-order model. A further model reduction is perform via principal component analysis (PCA) based on the structural optimization history.

An optimization is performed with the objective of counteracting wing flexibility, which directly affects induced drag and lift, by increasing wing rigidity at cruise condition.

It should be noted that DLM is used to generate the aeroelastic loads for the 2.5g and -1g load cases, while the surrogate model is used to take wing performance into account at cruise condition. Therefore, to correctly generate aeroelastic load it is important to reproduce on the DLM the correct wing twist law. This is achieved via DLM additive correction from CFD zero lift load distribution. This ensures a more realistic lift distribution for structural sizing and provides correct wing deflection improving the fidelity of aircraft performance evaluation.

437 Resolution enhancement of 3-D quantitative computed tomography image for proximal femur by using analogy between topology optimization and phenomenological bone remodeling.

Jung Jin Kim, In Gwun Jang

Since the analogy of structural topology optimization and phenomenological bone remodeling have been mathematically derived, topology optimization have contributed to quantitative understanding of bone remodeling process. In particular, a new concept of skeletal image resolution enhancement has been proposed based on this analogy. This approach reconstructs a high-resolution bone microstructure image through determining an optimal structure from a low-resolution image which represents a non-optimal structure due to a limited spatial resolution. In this study, topology optimization-based resolution enhancement are conducted using a clinical quantitative computed tomography (QCT) image of a proximal femur, which is one of the representative load-bearing bones. To obtain better numerical efficiency and more phenomenological results, a black-and-white filtering constraint and member size control are implemented in topology optimization.

438 Multi-objective robust design and evaluation of commercial vehicle components based on principal component analysis

Juhee Lim, Yong Sok Jang, Hong Suk Chang, Jong Chan Park, Jongsoo Lee

During the front-loading design stage, it is important to accommodate design uncertainties and its data scatter based on rational probabilistic approaches. Prior to probabilistic system optimization such as reliability based design optimization or probabilistic target cascading in the context of multidisciplinary design optimization, the rapid design and evaluation method should be necessary for the robust design of ride comfort and tilting convenience in a commercial vehicle cab suspension. The objective of robust design is to optimize the mean and minimize the variance that results from uncertainties represented by noise factors. It is expected to improve product quality and reduce manufacturing cost. The Taguchi method is widely used conventional approach for robust design as combining the experimental design with quality loss functions. However, this method can be only used in a single-response problem.

In this paper, we propose the principal component analysis (PCA) to optimize the multi-response problems in the Taguchi method. PCA is used to explain the variance covariance structure through linear combinations of the original variables. We compute the quality loss for each response and perform the PCA to determine the number of principal components. From the multi-response performance index, we can determine the optimal factor and level combination. The analysis of variance is used to investigate the effects of combined multiple performance constraints. In this work, control factors, noise factors and multiple responses are used for analysis of cab suspension; all with three level combinations comprising the design of the orthogonal array. Therefore, Taguchi experiments are performed, and the control factor-level combinations are chosen to provide sufficient information to determine the factor effects.

439 An Efficient Nonparametric Approach for Reliability-Based Design Optimization Using Tail Modeling

Sanghyun Park, Su-gil Cho, Woochul Lim, Cheonhong Min, Jaewon Oh, Tae Hee Lee

In terms of the reliability-based design optimization (RBDO), many designers are interested in an approach to accurately estimate in the tail region because they want to guarantee high target reliability located in tail region of the distribution. The generalized Pareto distribution (GPD) is widely known as one of the tail focusing approach. However, conventional GPD approach is inefficient because the GPD performs the random sampling in the body region meaningless and unnecessary for RBDO. In this study, therefore, we propose the efficient approach which only uses the sample points in tail region without considering the overall region. The proposed approach priorly performs the random sampling in the Taylor expansion surface. Because Tayler expansion gives the direction to violate the constraints, we can extract some sample points in the tail region out of the generated random sampling. By analyzing only extracted sample points, a tail-model based on GPD is performed. In the RBDO process, the GPD can give system reliability and sensitivity to optimizer at the higher reliability over the threshold of the tail-model. However, since it is sometimes out of the boundary where the tail-model is defined, information of the body region is needed. The approach approximates the information of the body region from censored data of the sample points in the tail region, which is possible to obtain the reliability through the tail-model considering the number of sample points for the tail region. The approach may be inaccurate in body region. The target reliability always is higher than threshold but the sensitivity in body region is enough to provide the direction toward the target reliability. In conclusion, we can perform an efficient nonparametric RBDO considering the number of sample points in tail region. The efficiency of proposed approach is demonstrated through the mathematical examples.

440 A topology optimization method for complex structures based on extended approximation concepts

Hai Huang, Haichao An, Haibo Ma, Shenyan Chen

This work presents an engineering method for structural optimization problems involving both topology and size variables. The method directly aims at the so-called discrete structures that are usually constructed with bars, beams, plates or other components, and it therefore can be applied to optimal layout and sizing of large-scale complex structures.

Based on the approximation concepts, a special branched multi-point approximate function is introduce, in which each size variable is defined in their upper and lower bounds when corresponding topology variable is 1 (component exists), and zero or extremely small value, in order to FE model no change, when the topology variable is 0 (component removed). Then a series of sequential approximate problems to the original structural optimization problem are constructed. To solve those approximate problems, a genetic algorithm (GA) is utilized to optimize the 0/1 topology variables that are contained in the problems, and when calculating individual member fitness values in GA, the second-level approximate problems that only involving retained continuous size variables are built, and then solved with dual methods. As a result, structural analyses are only needed before improving the branched approximate functions in the iteration cycles.

Numerical examples are given to illustrate the effectiveness of the method, including layout optimization of stiffeners and shell components in a frame-shell structure, as well as an application in a micro-satellite structure design. It can be found that the number of structure analysis required in the optimization process is dozens of times or fewer, even comparable to size-variable optimization.

441 Comparative Study between Different Strut's Cross Section Shape on Minimizing Low Wall Shear Stress along Stent Vicinity via Surrogate-based Optimization.

Narendra Kurnia Putra, Pramudita Satria Palar, Hitomi Anzai, Koji Shimoyama, Makoto Ohta

Endovascular stent has been employed to treat patients with intravascular diseases. Research on stent optimization is currently performed in order to find the best design in increasing the treatment efficacy. In this research, stent optimization is performed based on a finite element analysis method via Kriging surrogate model to observe the wall shear stress (WSS) conditions on the strut vicinity. Two configurations, rectangular and triangular are adopted as the cross section of a stent strut and compared to see each shape effects on WSS condition. Strut gap in range from 1 mm to 3 mm and the strut width from 0.05 mm to 0.45 mm are considered as the design variables for each cross section. Structure contact simulation between stent and vessel wall is carried out to obtain the 5% vessel expansion. Afterward, computational fluid dynamics simulation is performed to analyze the hemodynamic effect of stent design along with wall deformation. Minimizing the percentage low WSS area (WSS ¡ 1 Pa) relative to the length of stent deployment area is set as the objective function of this optimization since low WSS is believed to promote some problems such as atherosclerosis. In total, 45 and 42 simulation iterations are conducted respectively for both cross sections to develop the Kriging surrogate models for efficient global optimization. Besides the prediction of the optimized configuration, broader observation on its behavior within the design range is also well predicted. The optimized configuration has 2.99 mm gap and 0.1 mm width for the rectangular strut, and 2.00 mm gap and 0.99 mm width for the triangular strut. The triangular strut has better performance in reducing the low WSS area with 14.6% of low WSS area on its optimized design, compared to 18.6% of the rectangular strut. Moreover, the triangular shape strut produces more stable performance; most design configuration with the strut width of less than 0.35 mm can keep low WSS area at the minimum value.

442 Stacking sequence optimization and blending of composite laminates with a two-level approximation method

Haichao An, Hai Huang, Shenyan Chen

With excellent mechanical and physical properties, composite materials have gained wide applications in aerospace structures. For multi-region composite structures, their thicknesses are often tailored for lowest weight and best performance, known as ply-drop or blending problem. The stacking sequence optimization of composite structures is full of discreteness, and many methods based on genetic algorithms (GAs) are developed to address this problem, always requiring dramatic function evaluations. And it becomes more difficult when incorporating the ply continuity (the blending) requirement into the optimization design process. A two-level approximation method previously proposed by the authors proved to be quite efficient for stacking sequence optimization of composite laminates. In this work, this method is improved to consider blending rules in design of multi-region composite structures. With admissible ply angles, all regions are firstly given the same stacking sequences as an initial design. Based on this design, the problem is formulated which involves discrete 0/1 variables representing the absence/presence of each ply in the initial design and continuous ply thickness variables. To solve this problem, a first-level approximate problem is constructed using a branched multipoint approximate function which also involves mixed variables. GA is then used to optimize 0/1 variables. Crossover and mutation operators create the shared layers to satisfy the continuity of multiple regions, and local mutation is enforced to add/delete specific plies to make each region an efficient design. When calculating the individual fitness in GA, continuous ply thickness variables are optimally determined through a second-level approximate problem to be solved by dual method. A two-patch design is conducted to verify this method and a corrugated central cylinder in a satellite with multiple regions is optimally designed to show its applicability in practical engineering problems.

443 Bayesian parameter identification of turbulence model with complex parameter space

Noemi Friedman, Elmar Zander, Pradeep Kumar

In this contribution the calibration of the model coefficients of a novel turbulent flow model over porous media is considered. In the analyzed VRANS model the model coefficients to be calibrated are introduced to appropriately scale the impact of porous media on the overall flow. The developed method is herein given in two parts. In this first part the main focus is to develop a surrogate model for the simulation model as a first step for an efficient sensitivity analysis and calibration method. This surrogate model enables a computationally cheap evaluation of the flow characteristics for given values of model coefficients. The model also allows an efficient evaluation of sensitivities to variations of the model coefficients.

The surrogate modeling and the sensitivity analysis is herein shown for a specific porous-nonporous channel flow problem. For the surrogate different stochastic models were considered, compared and cross-validated. Evaluation of the Sobol- sensitivities of the flow solutions (velocity and Reynolds-stress fields) to variation of the model coefficients will be also presented.

Difficulties were imposed by the complex parametric domain containing holes corresponding to nonphysical setup of the coefficients. To avoid the identification of these a-priori unknown coefficient setups, and better understanding of the physical phenomena, a decision boundary separating physical and nonphysical parametric regions were identified by a support vector machine binary classification.

The calibration of the model coefficients uses expert prior knowledge by incorporating DNS data of the velocity field and the Reynolds stresses. The Markov Chain Monte Carlo method was used for the data assimilation combined with a polynomial based nonlinear Minimum Mean Square Estimator for speeding up the convergence of the random walk of the MCMC. The MMSE is herein applied by a low-rank representation of the measurement by proper orthogonal decomposition.

444 A Robust Metric in Optimization-based Approach for Statistical Model Calibration

Hyunseok Oh, Hwanoh Oh, Byeng D. Youn, Joon Ha Jung

Statistical model calibration is often used to maximize the degree of agreement between predicted responses from a computational model and observed responses from experiments. The adjustment of uncertain model parameters in the computational model can be achieved by employing an optimization-based approach. One of the key steps in the approach is to define an objective function (i.e., calibration metric) in the optimization process. In the preliminary study, it is shown that existing calibration metrics such as likelihood and Kullback-Leibler divergence have limitations for calibrating computational models efficiently and accurately. To this end, this study proposes a new calibration metric, namely, probability residual (PR). Mathematically, the PR is defined as the sum of the product of a scale factor and a squared residual. First, the scale factor is incorporated to relieve the numerical singularity problem that can leads to divergence in an unconstraint optimization process. Second, the squared residual that has a quadratic form is employed to enhance the convergence efficiency of the calibration metric. Thus ,it is guaranteed that a global optimum exists. To evaluate the performance of the proposed calibration metric, numerical examples are used. In summary, it is anticipated that the proposed calibration metric helps calibrate computational models in a robust and reliable manner.

446 Conditional expectation based spectral Bayesin filter for time-dependent and nonlinear systems

Bojana Rosic, Muhammad Sadiq Sararaz, Hermann Matthies

The estimation of unknown parameters of nonlinear system, especially chaos, is often difficult due to complexity of the model behaviour. In a probalistic manner the incorporation of new information through Bayes theorem has two constituents; the measurable function or random variable, and the probability measure. One group of methods updates the measure function or random variable, and the function. Traditional Monte-Carlo methods like Metropolis-Hastings and its variants are belonging to the first group of methods. They are based on serial sampling of posterior distribution in which many of samples are rejected. The major drawbacks of these methods are thus slow convergence rates, and loss of independence in sample series representing the posterior. To make the Bayesian identification feasible for partially-observed nonlinear systems, we present a novel procedure in which the approximated Bayesian nonlinear filter is designed from the variational problem associated with conditional expectation. The procedure updates the measurable function, i.e. random variable, in a functional approximation form by employing the powerful unvertainly quantification cimputational tools. The method will be presented on examples dealing with identification on nonliniear irreversible material phenomena in a multiscale framework, and estimation of parameters describing high-dimensional nonlinear dynamical chaotic problem.

447 Topology Optimization of Structure for Dynamic Property Considering Hybrid Uncertain Parameters

Wu Yi, He Zhi Cheng, Li Eric

In the design and manufacturing of mechanical components, the dynamic properties of continuum structure are one of the most significant performances. At the same time, the uncertainty is widespread in these dynamic problems. This paper presents a robust topology optimization (RTO) methodology of structure for dynamic properties with consideration of hybrid uncertain parameters. The imprecise probability uncertainties including materials, geometry and boundary condition are treated as an interval random model, in which the probability distribution parameters of random variables are modeled as the interval variables instead of given precise values. Two dynamic properties, including dynamic-compliance and eigenvalue, are chosen as the objective function. And the expressions of the dynamic-compliance and eigenvalue with interval random uncertainty and its sensitivities are derived. In this work, the bi-directional evolutionary structural optimization (BESO) method is adopted to find the optimal robust layout of the structure, and different excitation frequency or eigenvalue are discussed. A series of numerical examples are presented to illustrate the optimization procedure, and the effectiveness of the proposed method is demonstrated clearly.

448 Design optimization of tunable locally resonant elastic metamaterials

Bin Niu, Xiaolong Liu, Rui Yang

Metamaterials are generally considered as artificially designed structural materials with microstructures that present unusual properties. With the success of electromagnetic metamaterials, the research on elastic metamaterials has been attracting much attention. This paper deals with the design and optimization of the locally resonant elastic metamaterials for the suppression of vibration and wave propagation. The microstructure in the periodic metamaterial is composed of spring-like flexible components and elastic components. The number and positions of spring-like components and elastic components will be designed carefully. Due to the quite large size difference in the flexible spring-like components and the elastic components, the usual topological design of the material distribution in the microstructure is challenging to obtain the spring-like components, which is important to realize the locally resonant low-stiffness elastic metamaterials. The present study directly deals with the number and positions of spring-like components by transforming them into continuous variables so that the gradient-based optimization algorithm can be used. In fact, it can be considered that the topology optimization method is used to design the spring supports of elastic components. Analytical expression and numerical solution of the wave propagation in the periodic systems are obtained. The directional band gaps of the wave frequencies will be studied in the design optimization. Several numerical examples are conducted to validate the optimization formulations and demonstrate the design efficiency on suppression of vibration transmission.

449 Optimization of stepped plates in the elastic plastic range

Jaan Lellep, Julia Polikarpus

Thin-walled beams, plates and shells are widely used in the engineering. Thus, the saving of the material and increasing the stiffness or load carrying capacity of plates are of primary concern of engineers. In the literature one can find plenty of solutions of optimal design problems regarding to elastic or pure plastic materials. However, much less attention is paid to optimal design of structures in the elastic plastic range.
The problems of parametrical shape optimization of axisymmetric thin-walled plates subjected to the transverse pressure are treated in the present paper assuming that the plates are operating in the range of elastic plastic deformations. Various formulations of optimization problems regarding to circular and annular plates made of homogeneous and composite materials are discussed. Among these the minimum weight problems, also the problems of minimization of displacements at certain points of the plate as well as various parametrical optimization problems are considered. In order to get the conditions of optimality the variational methods of the theory of optimal control are employed.
The plates made of of materials which correspond to linear and non-linear yield surfaces, respectively, are treated separately. In the case of piece wise linear yield surfaces (for instance, in the case of yield surface corresponding to Tresca yield criterion) the direct problem of determination of the stress strain state of the plate is solved analytically. The optimization problem is transformed into a non-linear programming problem. The latter is solved with the aid of existing computer codes.

450 Efficient density based topology optimization using dual layer element and variable grouping method for large 3D applications

Jaeeun Yoo, Ikjin Lee

Topology optimization is the most useful method to perform the conceptual design at the early development stage. Various topology optimization methods are developed until now, such as "SIMP", "BESO", "Level-set" and others. Density method such as SIMP is widely used due to its simplicity and expandability. But density method needs a lot of computation time to acquire smooth boundary result in case of complex 3D applications.
In this paper, efficient density based topology optimization method is proposed. FEA(Finite Element Analysis) meshes are distinguished from topology density element in this method. FEA element stiffness can be integrated by density element stiffness summation using the MTOP(Multi-resolution Topology Optimization) method, and this dual layer element approach can reduce FEA computations. In spite of FEA time reduction, numerous density element cause the increasing of calculation time during the optimization process. Therefore variable grouping method is introduced. Variable grouping method is performed by multiplication of sensitivity function and density value. Grouping variables are not related to spatial closeness, therefore grouping variables can represent the complex geometrical topology. Variable reduction process is performed according to histogram of multiplication of sensitivity and density variable like a contrast enhancement in the image processing. These process is similar to image display process. Even if 16bit dynamic range image data, most image viewer shows translated 8bit image data using histogram reduction because most of display monitor can represent 8bit dynamic range.
The result of compliance minimization example is presented for the large 3D application. Due to Dual layer element approach and variable grouping method, computation time of the density based topology optimization can be extremely reduced than previous method.

451 Enhanced Firefly Algorithm with Implicit Movement

Ronald Bartz, Sierk Fiebig, Thilo Franke, Paul Falkenberg, Joachim Axmann

The question for an optimal solution to a certain real-world problem often turns into a complex optimization problem. The sizing of the cross sections for bars of a truss structure is generally hampered by interdependencies. This prevents local search methods from finding a sufficient optimum. For those issues, there is a demand for fast and reliable global optimization algorithms. The Firefly Algorithm is a swarm-intelligence-based method frequently used for solving multi-modal optimization problems. The algorithm maintains a set of individuals, each corresponding to a point within the solution space. During the optimization process, the individuals move within the solution space under certain rules in order to find the global optimum. This paper presents an enhancement of the Firefly Algorithm by an implicit backward Euler movement. Therefore, in each iteration a linear system of equations must be solved to determine the new positions of the individuals. To evaluate the performance of the implicit movement, it is applied to continues benchmark optimization functions. The optimization process is compared to the basic Firefly Algorithm to specify the effect of implicit movement. Furthermore, a discrete parameter optimization of a ten-bar truss in the sense of a weight reduction is carried out. The optimization results are compared to the basic Firefly Algorithm as well as to the results of four state-of-the-art algorithms. The implicit movement provides an intuitive and an easy to implement modification of the Firefly Algorithm. Simulation results show that the implicit movement causes a significant improvement in the convergence behavior compared to the basic Firefly Algorithm and outperforms state-of-the-art algorithms in terms of the solution quality and convergence behavior. Due to its generality, the proposed implicit movement can be implemented to several swarm-intelligence-based algorithms and offers a promising universal approach for enhancement.

452 Multi-Material Topology Optimization of Automotive Component Structure

Youngsuk Jung, Seungjae Min

This paper presents a topology optimization process of the automotive component structure for considering multi-material design. As the design of the lightweight structure is required to increase the energy efficiency, interest in the structural optimization method that can take into account multi-material design is increasing. A multi-level set model based topology optimization method, which can easily consider multi-material and does not have an intermediate density, is widely used. However, in the case of commercial software such as OptiStruct or GENESIS, which is often used in industry for structural optimization, topology optimization method considering multi-material design has not yet been applied.
In this paper, we propose a multi-material topology optimization process using the output data of commercial software. Firstly, the design sensitivities are calculated from the analysis result output data such as the element strain energy, the nodal displacement, the element internal force and the modal strain/kinetic energy. Secondly, the design variables are updated using the multi-level set model based topology optimization method. Finally, the material property of each element is changed based on the signs of level functions, and perform finite element analysis repeatedly until the solutions converge. The proposed design process is applied to design of the automotive control arm structure considering two materials of steel and aluminum. The optimization problem is formulated that minimizes the mass subject to displacement constraints.

454 Design Optimization of the IPM Motor for Improving Torque Performance at a High Driving Temperature Using Circuit-Field Coupled Analysis

Sunghoon Lim, Seungjae Min, Kazuhiro Izui, Shinji Nishiwaki

A Nd-Fe-B magnet, which has been widely used in an interior permanent magnet (IPM) motor due to its strong magnetic property, has demagnetizing characteristics at high temperature and it is important to consider the temperature-dependent property in the motor design. Since the heat source of a driving motor is influenced by the magnetic flux in the motor core and the magnet temperature affects on the magnetic performance of the motor system, a fully coupled analysis step is necessary to estimate the magnetic-thermal characteristics of the motor and to perform the design optimization. Therefore, the finite element (FE) based optimization techniques, which have been proposed for a detailed shape design of the motor, can cause a lot of computational time to solve such multi-physics problem.

This paper proposes a new design optimization method that incorporates an efficiency of the magnetic equivalent circuit (MEC) and an accuracy of the FE analysis for improving the magnetic-thermal coupled performance of the IPM motor. The driving temperature and the magnetic performance of the motor are estimated by the lumped parameters in the MEC, rapidly, and the FEs are used to figure out the exact flux distribution around the airgap, which can greatly affect the torque performance of the motor. The optimization problem is formulated to minimize the harmonics of the magnetic flux in the airgap with the design constraints for the average power and the torque ripple. In the FE-based design domain, a level set function is employed to represent a detailed structural design of the steel core. The proposed design process consists of two optimization steps to calculate the optimal circuit parameters for improving the torque performance of the motor and to obtain a specific structural boundary in the design domain. To demonstrate the usefulness of the proposed method, a motor design problem with the ND-FE-B magnet will be provided.

455 Multi-objective Optimization Using Adaptive Weight Determination Scheme Based on Concept of Hyperplane

Namhee Ryu, Seungjae Min

As a design problem should consider various performances, it is hard to find an optimal design that satisfies all performances at once. To overcome this problem, multi-objective optimization method has been researched to obtain design candidates which are the sets of Pareto optimal solutions. Among many different methods, weighted sum method and ε-constraint method are widely used for their convenience in use. However, these methods should be carefully used as a designer should define the values of weights or constraints to find different Pareto optimal solutions. Since distribution of weights does not guarantee the evenly distributed solutions in objective domain, weights needs to be systematically determined considering the obtained solutions so that new Pareto optimal solutions can be found efficiently. Therefore, this paper presents a multi-objective optimization using new adaptive weight determination scheme. Optimal solutions on Pareto frontier are gradually found with different weights, and values of weights are adaptively determined considering the positions of previously obtained solutions. For N-objective problem, hyperplane is constructed in N-dimensional space by using previous solutions and coefficients in the equation of the hyperplane are used as next weights so that new optimal points can be found on Pareto frontier. To confirm the effectiveness of the proposed method, different types of benchmarking problems including convex, concave, and three objectives problems are tested. Hypervolume indicator is used to quantitatively evaluate the proposed method and it is confirmed that optimal solutions that are evenly distributed in Pareto frontier can be obtained.

456 Design of 3D Woven Materials for Enhanced Dynamic Properties

Hak Yong Lee, David Mills, Timothy Weihs, Kevin Hemker, James Guest

Manufacturing approaches capable of controlling the microscale architecture of materials provide exciting opportunities for creating new materials with tailored and optimized bulk properties. This talk will consider 3D weaving as a means for fabricating porous metallic lattices. In this process, wires are simultaneously placed in two orthogonal directions, which are bound together using wires running in the third orthogonal direction. These lattices have been shown to have numerous desirable properties, from mechanical to heat transfer properties. Herein we examine the dynamic properties of these lattices and use optimization to enhance the vibration suppression capabilties. Specifically, we formulate a topology optimization ground structure approach to optimize the distribution of wire stiffness and mass within the woven material to supress bulk material motion at prescribed excitation frequencies. Several design examples are presented along with corresponding experimental testing conducted on a Dynamic Mechanical Analyzer using samples fabricated from 200-micron diameter copper wires.

457 Phononic Band Gap Maximization for Broadband Energy Harvesting around A Target Driving Frequency

Guilian Yi, Yong Chang Shin, Heonjun Yoon, Soo-Ho Jo, Byeng D. Youn

Topology optimization of phononic band gaps (PBG) produces periodic designs of phononic crystal (PnC) exhibiting the largest frequency bands within which mechanical waves (i.e., elastic and acoustic waves) cannot be transmitted. The known solutions are found by assuming that the prohibited incident waves be any frequency in the band gap. Engineers in the area of energy harvesting published a research on converting mechanical waves into electric power using piezoelectric materials, which maximizes the amount of output power subject to a given energy density of input waves (Yoon et al.2016). In practice, most realistic mechanical waves have physical uncertainty such as frequency fluctuations. If the wave frequency lies inside the PBG, waves in a concave-shaped PnC structure can be reflected and focused toward a small area for energy harvesting. Since a large band gap allows a large variation in the driving frequency, a PnC with the target driving frequency centralized in its largest band gap is thus of immense significance for promising robust broadband energy harvesting (BEH).

Although many published studies are conducted on topology optimization of PBG, as well as BEH using PnC or other metamaterial-inspired structures, no research has been conducted to realize both. We herein present the maximization of PBG for BEH around a target driving frequency by means of topology optimization. Band gaps of elastic waves propagating in 2D bimaterial PnC are studied. The optimization problem is formulated to maximize the band gap with a constraint on centralizing the target driving frequency in the bang gap. A linear interpolation scheme is used to control the elastic properties. The adjoint method is used for sensitivity analysis of multiple eigenvalues. A gradient-based optimization technique integrated with the finite element method is used for execution of the band gap maximization. For comparison purpose, band gap maximization designs without constraints are also studied.

459 Topology optimization considering large elastoplastic deformation with kinematic hardening behavior

Hiroya Hoshiba, Junji Kato

The purpose of this research is to develop a topology optimization method to improve energy absorption performance. Regarding topology optimization for maximizing energy dissipation due to elastoplasticity, kinematic hardening behavior in addition to finite strain theory has not yet been considered. Therefore, we try a simple approach of incorporating an advanced elastoplastic material model into the traditional topology optimization framework.

In formulating finite strain elastoplastic model including kinematic hardening law, it is known that behavior of back stress rate as an internal variable has crucial instability like stress oscillation. To avoid this problem, we described elastoplastic constitutive equations with reference to the plastic intermediate configuration. This leads to a new formulation for sensitivity analysis and optimization algorithm is operated by analytically derived sensitivity therefrom. And some optimization calculations are carried out to verify practical concerns: accuracy, computational cost, convergence of solution.

461 A New Calibration Metric to Improve the Solution Feasibility of Calibration Problems: Marginal Probability and Correlation Residual (PCR)

Wongon Kim, Guesuk Lee, Hyejeong Son, Guilian Yi, Byeng D. Youn

To improve the model prediction accuracy, model calibration becomes of great importance. Often, due to a great deal of random inputs in the complicated computer models, statistical model calibration problems struggle with infinitely many solutions, of which most are physically infeasible. That is because the conditions given in the problems do not suffice to determine a feasible calibration solution. Conventionally, a model calibration problem is solved by minimizing a set of calibration metrics. The metric is generally defined as statistical similarity or difference between simulation and experiments (i.e., likelihood, probability residual (PR)). It is found that considering the correlation between multivariate responses is a key to resolve the solution feasibility issue. A new calibration metric, namely probability and correlation residual (PCR) is herein proposed. The proposed metric can improve the solution feasibility of the calibration problems because the metric eliminates infeasible solution regions.

In this research, the effectiveness of the proposed method is demonstrated with a simple calibration problem and a practical automotive engineering problem. The experiment of the automotive problem is conducted to measure principal strains at reference and critical spots under static loading conditions. Through the experimental observations, diverse sources of uncertainty are understood, such as force direction and material properties. They are considered as a set of calibration variables in the statistical calibration, which conducts the optimization with a Kriging-based Monte Carlo simulation. The solution feasibility is validated by showing that the predicted maximum von Mises stress spot coincides with the observed one. Additionally, the displacement at a loading point is used to check the validity of the calibrated computer model. To the end, the PCR calibration metric yields a feasible solution whereas the PR metric does not.

462 Topology optimization of components and embedded reinforcements using discrete object projection

Saranthip Koh, James K. Guest

Many engineering components and materials gain strength and functionality through strategic placement of reinforcing objects. Often these objects are selected 'off-the-shelf' and thus come in fixed size and shapes, such as fibers with circular cross-sections, and are not permitted to overlap due to physical geometry or functionality requirements. Herein we investigate the use of Discrete Object Projection (DOP) for optimizing the distribution of discrete reinforcing objects within a structure [1-3] and specifically extend the DOP approach to simultaneously optimize the component topology. This essentially adds an additional material phase to the DOP topology optimization problem. As in typical projection-based approaches, all geometric constraints, including length scales of the objects, spacing between the objects, and length scales of the component are achieved through the projection functions without additional constraints. The proposed algorithm is demonstrated on benchmark problems in structural designs where the elastic stiffness of structures is to be enhanced by optimizing the layout of stiff inclusions. Various inclusion size and shapes, and combinations thereof, are considered.

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463 Imaging and pattern formation for vector fields using partial differential equations

Atsushi Kawamoto, Tsuyoshi Nomura, Tsuguo Kondoh, Mario Petrovic, Shinji Nishiwaki

This paper deals with imaging and pattern formation techniques in terms of practical implementation utilizing automated solutions of partial differential equations (PDE). We propose a method that generates a line and space pattern for a given vector field in the time evolution of PDE based on Line Integral Convolution and Reaction Diffusion Equations. All programs are implemented in COMSOL Multiphysics. From an agility point of view, the proposed method is advantageous because all the necessary elements are already included in the software package. Therefore, the proposed methods can be implemented by simply describing equations. The effectiveness of the proposed methods is confirmed through numerical examples.

In multiscale heat conduction design problems, the orientation angle distribution of the anisotropic material (macro variable) is designed. As a micro expression, for instance, one can use a texture pattern, such as flow lines. In that case, from the manufacturing point of view, it is desirable to make the flow line density as uniform as possible (ideally equal intervals). For generating a line and space pattern, Line Integral Convolution and a reaction-diffusion model can be used. In this study, when a vector field is given in a plane, using the above-mentioned time evolution equation, we propose a method for generating an approximate equal interval streamlines along the vector field.

464 Application of multi level optimization algorithms

Laszlo Kota, Karoly Jarmai

In our industrial researches we often face very difficult problems where ordinary algorithms fail to find the global optimum. Mostly they have difficult, high-dimensional count, very large design space, where even the concept of direction and distance are non-existent and have to be defined, the neighbourship in the design space also needs definition. In these cases, these terms are often defined and calculated by heuristic functions. At these problems the applied optimization methods often fail, they stuck in local optima, working very slowly and find local optima. So we decided to try to link optimization methods and create multi-level optimization methods to cope these problems. As a base concept in the first stage we use some simple, fast, rapidly converging algorithm, after that some finer grade algorithm like population based swarm optimization methods. In this paper, we will show and evaluate some multi-level optimization methods tested on several test functions, comparing the convergence and computational needs.

465 Size and shape optimization of hybrid energy absorbers for crashworthy aircraft structures

Jacobo Díaz, Javier Paz, Luis Romera

The combination of metallic and composite materials in crash-absorbing parts is a solution to improve crashworthiness response on an aircraft without increasing its mass significantly. Vertical struts, which connect the passenger cabin floor and the lower part of the fuselage, can be designed to function as energy absorbers for middle-to-large size aircraft. During an impact, these vertical tube-like structures are exposed to axially-dominated compressive loads. Its effect on the crashworthiness of the aircraft is greatly dependent on their overall stiffness: while a rigid strut helps the lower part of the fuselage to dissipate more energy, the cabin floor would endure more if flexible struts were fitted. However, and despite their acute effect on the aircraft's crashworthiness performance, few studies conducted up to date consider a continuous trade-off between the energy absorbed by the strut and its stiffness.

New designs arise from the combination of cores made of polymeric composites or synthetic foams with aluminum enclosures. While the cores provide specific strength and stiffness, the metallic enclosure adds a ductile and progressive collapse mechanism to the final design. This research describes the design optimization of an aircraft hybrid energy absorber. The basic layout consists of a hollow metallic tube with a honeycomb-shaped inner structure, which can be filled with synthetic foam. The design variables are the tube's wall thickness and the honeycomb's cell shape, size and wall thickness. Several objective functions and design constraints are proposed, which consider the energy-absorption performance of the strut as well as the survivability of passengers. Due to the large computational cost of running each analysis, a surrogate-based optimization approach is used. Optimum designs for different design situations show an increase of up to 25% in specific energy absorption and a decrease in peak force of up to 40%.

466 Topology Optimization Considering Filtered White Noise Stochastic Excitations

Yang Yang, Mu Zhu, Michael Shields, James Guest

This work addresses the challenge of topology optimization for continuum structures subjected to non-white noise stochastic dynamic excitation. The structures response (and sensitivities) are modeled as filtered white noise using the augmented state space formulation in the frequency domain. The Solid Isotropic Material with Penalization Method is used together with the Heaviside Projection Method to achieve a clear distinction between solid and void regions in the structure, and the gradient-based optimizer Method of Moving Asymptotes informed by sensitivities of the real and complex eigenvectors is used to evolve the design. The algorithm is demonstrated on design problems of minimizing the variance of stochastic response under a volume constraint and several numerical examples are provided to show the effectiveness of the method. Solutions are compared to conventional maximum stiffness solutions and, as to be expected, show markedly improved response in stochastic dynamic environments.

469 Accuracy Improvement of Cyber-Physical Robots (CPR)

Po-Chun Juan, Wei-Hao Lu, Shu-Ping Lin, Po Ting Lin

The concept of Cyber-Physics Systems (CPS) has been introduced to machining and manufacturing in the past few years. CPS creates a virtual copy of the physical manufacturing process and monitors the real one simultaneously. The differences between the virtual and real processes are critical for decision making and production control. Internet of Things (IOT) collects the physical process from the real world and builds a real-time communication with humans. Cloud computing executes real-time calculations of data analysis, mathematical modeling, optimization and decision making. The successful integration of CPS, IOT and cloud computing makes a factor smarter and ready for Industry 4.0. Cyber-Physical Robots (CPR) play important roles in the manless smart factory. Compared with conventional robot systems, CPR operates and completes tasks autonomously. A series of numerical simulations, mathematical models and optimizations provide the motion sequence of CPR. The error between the robot movement and the desired trajectory is to be sensed or measured and updated to the CPS for real-time corrections. The absolute error of robot position is inevitable due to complex robot dynamics and uncertain load conditions. Real-time position measurement apparatuses such as laser range finder and tracking devices are mostly expensive and requires experimental set-up. This paper presents an efficient method to measure the absolute robot position in real time using 3 sets of cable extension position sensors. The three-dimensional absolute position error is then modeled by a Kriging response surface with respect to the desired robot position and load condition. In our implementations, the CPR controlled by the compensated motion commands performs $\tilde{9}0\%$ greater accuracy in absolute positioning. The proposed Kriging-based accuracy improvement of CPR will greatly reduce the computation time of model update and motion adjustment in CPS.

471 Investigation and Comparison of Alternative Material Property Models for Density-based Topology Optimization

Mark Christian E. Manuel, Po Ting Lin

Density-based methods in topology optimization relies on material property models in which the design (or density) variables are related to the effective material property, depending on the physics of the problem considered. However, there are only a limited amount of paper which discusses alternative material interpolation models and penalization, especially in the context of heat conduction topology optimization. Probably the most popular material property model used for topology optimization is the SIMP interpolation or 'power-law' model. The question on the physical relevance of the solutions obtained, especially for intermediate solutions where the density values are 'gray' or between 0-1, has been addressed by realizing material composites which can perform based on the material property model considered. However, there is an abundance of other material property models which can be used to relate the density variable to the effective material property. In this paper, we present 6 fixed material interpolation models and 6 different tunable material interpolation models. We highlight differences and similarities in search spaces which lead to optimal but unique solutions. This effect is demonstrated through the access problem in heat transfer. Differences in the material property models are exemplified in the different results obtained in the cases where the search space is distinct. It can be said that each of the tunable material property model exhibit a unique characteristic which can be exploited for different physics problems.

472 Is Cortical Bone Defect Healing a Structural Optimization Process?

Chander Sen, Jitendra Prasad

Distribution of various tissue phenotypes in vivo during cortical bone defect has been hypothetized to be a result of an inherent structural optimization process. The hypothetized aim of the healing is to minimize strain energy subject to constraint on the volumes of the different tissues involved in bone healing and also on the stresses developed around the callus under physiological loading condition. To test this hypothesis, a simplified finite element (FE) model of a long bone (viz. tibia) was earlier developed using 16-noded elongated brick elements, which uses cubic interpolation functions along the length of the bone (z-direction) and linear interpolation in transverse (x and y) directions. Every element spans the whole length of the bone. The whole bone is, thus, geometrically represented as a prismatic beam by tiling these elongated brick elements in x and y directions only. This representation of geometry makes it easier to apply physiological loading, which is approximated to be a combination of normal and cantilever loads. A unicortical defect in the bone is represented by removal of elements from the defect site. The objective of optimization is to minimize compliance by adding various tissues at the space not already occupied by the original cortex. The allowed tissue phenotypes are hard tissue (i.e. bone), granulation tissue (i.e. connective tissue and blood vessels), bone marrow and no tissue at all (i.e. void). This is thus a four phase topology optimization problem, where variables are the densities of each of the elements of descretized design space. Each variable can take one of four densities corresponding to the four tissue phenotypes. The solution of the optimization problem gives tissue distribution around the damaged site, which is similar to the tissue distribution found in vivo during cortical bone defect healing. Thus, the result supports the hypothesis that bone fracture healing is basically a structural optimization process.

473 Multi-scale concurrent material and structure design of a metal matrix for heat transfer enhancement in phase change materials

Alberto Pizzolato, Adriano Sciacovelli, Vittorio Verda

Designing thermal energy storage units with high energy and power density is a key objective for accommodating more renewable generation. The low thermal conductivity of phase change materials (PCMs) demands for finely tailored metal matrixes or foams to increase the amount of energy that can be stored/retrieved in a given amount of time. Previous design studies have explored a limited design space and never analyzed nor optimized the micro-structural topology of the matrix.
This paper proposes for the first time a multi-scale design optimization of the PCM-metal composite and the metal matrix layout. The material constitutive law of the heat transfer structure at the macro-scale is governed by the layout of a representative volume element at the micro-scale, where a universal material layout is considered.
The phase change problem is solved through a fixed-grid finite element method based on the enthalpy-porosity model, which accounts for natural convection in the liquid at the macro-scale. Topology optimization at both scales is formulated according to a density based approach.
The optimization results indicate that: (i) the topology of the micro structure strongly influences the device performance and the macro structure layout; (ii) the multi-scale design approach yields remarkable improvements compared to a standard mono-scale approach; (iii) the optimized micro-structural layout is slightly sensitive to changes in the operating conditions.

474 Topology optimization of incompatible isogeometric stiffened structures using evolutionary algorithms

Malte Woidt, Kay Sommerwerk, Matthias Haupt, Peter Horst

Topology optimization with evolutionary algorithms is an iterative process. Each step includes modification of geometry, mesh generation, analysis and postprocessing to compute a fitness value. For complex geometries, the steps modification of geometry and mesh generation cannot be automatized in a general, problem unspecific way. To simplify these steps and to increase robustness the concept of the isogeometric analysis (IGA) is incorporated into an optimization environment using evolutionary algorithms. Here stiffener topologies of stiffened panels are targeted.

For a FEM approach with knot incident meshes the geometry has to be remeshed if the stiffener pathes and in consequence the topology changes arbitrarily. The IGA directly uses the NURBS output of the CAD based geometry modification step for analysis. Therefore no distinct meshing step needs to be performed. The analysis model can be directly modified by thoroughly tested algorithms from the CAD world.

To handle T-junctions, e.g. the connection between panel skin and stiffener, a Lagrange Multiplier method [1] is proposed that connects stiffener and panel skin along the stiffeners path without the need for equivalent discretization on both sides. This method is well suited for optimization as the stiffener path can be modified without changing the discretization of the panel.

To show the concepts feasibility and properties, the mass to eigenfrequency ratio of a stiffened panel is optimized. Each stiffener path is linearly interpolated between a set of root points. The locations of all root points are the design variables and changed during optimization. As this is a global non-linear optimization problem an evolutionary algorithm used.

[1] Woidt, M.; Sommerwerk, K.; Haupt, M.C. & Horst, P.: Modelling stiffened lightweight structures with IGA via mortar methods. ECCOMAS Congress on Computational Meth. in Appl. Sciences and Eng., Crete Island 2016

475 Integrated layout and topology optimization design

Jihong Zhu, Weihong Zhang

The integrated layout and topology optimization of multi-component structure systems is an idea to find corresponding design of the components' layout and structural patterns. The purpose of this presentation is to provide an introduction and overview of the state of the art of the integrated layout and topology optimization technologies. A brief introduction to the early developments of the integrated layout and topology optimization is presented firstly. Extended integrated layout and topology optimization methods dealing with the multi-frame and multi-component fuselage structure systems design are then presented. Considering an aircraft or aerospace fuselage system including main structure, numbers of frames and featured components located on the frames, a simultaneous optimization procedure is proposed here including geometrical design variables of components and frames as well as topological design variables of main structure and frame structures. The multi-point constraints (MPC) scheme is used to simulate the rivets or bolts connecting the components, frames and structures. The finite circle method (FCM) is implemented to avoid the overlaps among different components and frames. Furthermore, to deal with the difficulties of large numbers of non-overlapping constraints, a penalty method is used here to compose the global strain energy and non-overlapping constraints into one single objective function. To guarantee the fuselage system's balance, the constraint on the system centroid is also introduced into the optimization. Different numerical examples are tested and the optimized solutions have demonstrated the validity and effectiveness of the proposed formulation.

476 Topology Optimization for Photopolymer-based Additive Manufacturing

Mikhail Osanov, James Guest

The technological advancements of additive manufacturing techniques have made it possible to fabricate structures with complex topologies, providing new opportunities in design. Topology optimization provides the means of leveraging these opportunities as it is a systematic, free-form, computational approach to the design of structures. To fully leverage additive manufacturing capabilities, however, topology optimization algorithms must account for limitations of the fabrication process, from manufacturing constraints to associated variations. This paper will discuss new developments in design for additive manufacturing, specifically focusing on the constraints associated with photopolymer processes and a projection-based approach for mimicking the layer-by-layer nature of the fabrication process. The method takes into account the anisotropic nature of fabricated features and aims to eliminate the need for post-processing of solutions. Problems will utilize the SIMP interpolation, Heaviside Projection Method (HPM) and will be solved using the Method of Moving Asymptotes (MMA) optimizer. The method can further be combined with the projection-based method for achieving overhang constraints [1], thereby eliminating the need for internal support structures that must be mechanically removed in post-fabrication.

[1] Gaynor A.T. and Guest J.K. (2016). Topology optimization considering overhang constraints: Eliminating sacrificial support material in additive manufacturing through design. Structural and Multidisciplinary Optimization 54(5):211-233.

477 Optimal design of galvanic corrosion protection systems for jacket wind turbine support structures

Ali Sarhadi, Asger Bech Abrahamsen, Mathias Stolpe

Galvanic anodes cathodic protection system (GACP) is one of the common methods for corrosion protection of offshore wind turbine foundations. Defect in the corrosion protection (CP) system or its failure can affect the lifetime of the wind turbine foundation, considerably. Thus, designing an efficient and cost effective CP system is of crucial importance for offshore wind support structures. The current manual CP design approach is usually time-consuming and results in higher cost of the CP system. Furthermore, the position of the anodes on the support structure, as an influential parameter on the performance of the CP system, is not determined in the standards. This is of even more importance for jacket support structures than their counterparts namely monopiles and suction buckets, as the jacket structures are more complicated and hence its modeling as well as design of a CP system with uniform corrosion protection over the structure is more challenging. Thus the current work deals with optimal design of GACP systems for jacket structures. A cost optimization problem with the number and dimensions of the anodes as design variables and the nonlinear constraints in the standard as design constraints is formulated. A MATLAB routine is developed for first optimizing the number and dimensions of the anodes, then distributing the anodes on the structure and finally calculating the electrochemical potential on the structure by calling a boundary element COMSOL solver. Using the boundary element method instead of finite element method for potential calculation on the jacket structure reduces the computational cost, considerably. Design optimization is performed for CP systems with different coating type, anode material and type. Finally, the best designs are selected by comparing both protection performance and the design cost. The obtained results show the efficiency of the optimization method for reducing the cost of CP systems as well as improving their performance.

481 Design of a controlled piezoelectric positioner with vibration suppression by using TOM

Mariana Moretti, Emílio Silva

Modern electronic devices require light-weight, less stiff and therefore more susceptible to external disturbances components. On the other hand, these devices, such as hard disk reading arms and atomic force microscopy cantilever probes, are developed for higher precision actuation. Therefore, this works proposes the design of a piezoelectric positioner with reduced vibration amplitudes at its operation point. Previous works have applied the Topology Optimization Method (TOM) to improve the piezoelectric shunt damping of a hard disk drive, or to distribute piezo-ceramic material over a base structure associated with a controller, in both cases targeting the structure vibration suppression. However, instead of obtaining a discontinuous patches distribution of piezoelectric material with a different voltage input each, it would be more realistic to have equipotential, fixed piezoelectric electrodes, while the optimization procedure seeks the base material distribution. In addition to that, the advantage of the base structure material distribution is that the vibration attenuation does not depend exclusively on the feedback constant gain to amplify the piezoelectric coupling coefficient and generate the appropriate feedback voltage input, increasing the structure damping. Instead, the optimized base structure layout helps to reduce the compliance of the overall structure. In this case, the objective function implemented in this work aims to minimize the vibration energy of a target degree-of-freedom at a specific point of operation for the positioner. The problem is subject to a volume constraint, the dynamic equilibrium equation and the initial conditions for a time-domain transient analysis. The SIMP model and the SLP algorithm are employed for the optimization procedure and 2D results for different velocity feedback control gains are analyzed.

483 Topology optimization of continuum structures under the variance constraint of reaction forces

Tong Gao, Libin Qiu, Weihong Zhang

This work focuses on the design constraint to the reaction forces at the specific fixed boundary, i.e., the reaction forces between an elastic solid and its foundation. According to engineering experience, uniform reaction forces usually benefit the structural performance, i.e., uniform stress distribution in the connectors or welds. Particularly, in the long-term usage of high- or ultra-precision machines, an uniform distribution of vertical reaction forces over the pedestal supports greatly avoid non-uniform deformations of the supports that deteriorate the levelness of the bench surface and the machining accuracy. Therefore, it is of great importance to improve the uniformity of reaction forces through topology optimization.

The variance of the reaction forces at the boundary between the elastic solid and its foundation is firstly introduced as the quantitative description of the uniformity of the reaction forces. Base on the traditional formulation of the compliance minimization subject to the volume constraint, the variance constraint of the specific reaction forces is added. Its upper bound is determined by a relaxation of the variance value obtained in traditional optimization formulation. By means of the adjoint method, the sensitivities of the variance of the reaction forces are derived by one additional finite element analysis.
Numerical tests indicate that variance constraint of reaction forces could reduce the maximum value and improve the uniformity of the reaction forces, to some extent. However, if the upper bound of the variance constraint of reaction forces is too small, the optimization process might fail to find the optimal solution and the variance constraint might be violated.

484 esign of Manufacturable Multiscale Structures using Connected Morphable Components based Topology Optimization

JIaodong Deng, Wei Chne

The advances of manufacturing techniques, such as additive manufacturing, have provided unprecedented opportunities for producing multiscale structures with intricate latticed/cellular material microstructures to meet the increasing demands for parts with customized functionalities. However, there are still difficulties for the state-of-the-art topology optimization (TO) methods to successfully achieve manufacturable multiscale designs with cellular materials, partially due to the disconnectivity issue of neighboring material microstructures. In this paper, we propose an innovative multiscale TO design framework based on the concept of connected morphable component (CMC) to design manufactuable 2D multiscale structures. The key component of the proposed framework is an effective linkage scheme that guarantees smooth transitions/connectivity between neighboring material microstructures (unit cells). Using the CMC based TO, the number of design variables is greatly reduced which makes multiscale TO design a manageable all-in-one optimization problem that can be handled using conventional optimization algorithms. Mathematical homogenization is employed to calculate the effective material properties of the porous materials and to correlate the macro/structural scale with the micro/material scale. As a result, we illustrate the use of the proposed CMC based multiscale TO methodology for designing multiscale structures made of well-connected material microstructures with different topologies as well as multiscale structures made of graded material microstructures with a similar topology.

485 Multi-lateral topology optimization for lattice structure under material uncertainties

Yu-Chin Chan, Kohei Shintani, Wei Chen

Recent advances in additive manufacturing have enabled the manufacture of hollow shapes with complex external geometry and multiple materials using networks of small periodic cells known as lattice structures. The porosity and high number of elements in these structures generate lightweight designs with improved performance and functionality. This paper proposes a design approach for lattice structures considering both multi-material design and uncertainty in material properties. A density based multi-lateral topology optimization method is applied to find the optimal geometry and material layout. For robustness of structural compliance against uncertainty in material properties, a weighted sum of the mean and standard deviation is chosen as an objective function. To estimate statistical moments by the material uncertainty, the univariate dimension-reduction (UDR) method combined with Gauss-type quadrature sampling is employed. The numerical example demonstrates the efficiency of the proposed approach and the effect of material uncertainty on the robust design results.

486 Multi-Material Topology Optimization of Periodic Cellular Materials

Josephine Carstensen, James Guest

Additive manufacturing technologies have advanced significantly in recent years enabling the creation of increasingly complex periodic cellular materials, including topologies with multiple base materials. Multi-material topology optimization offers a means to leverage these new manufacturing possibilities. In this context cellular materials refer to materials with a unit cell topology that is periodically repeated throughout the bulk material. Topology optimization has previously been used to design single solid phased cellular materials with a range of extreme linear mechanical properties including elastic moduli, thermal conductivity and expansion, and fluid permeability, among others. In such problems, an inverse homogenization approach is used where upscaling, typically numerical homogenization, relates the unit cell behavior to the effective material properties. The lack of a recognized homogenization law for nonlinear properties, however, poses a significant challenge for expanding the design formulation to include nonlinear mechanics. In this work, an algorithm will be presented that enables multi-material topology optimization for unit cell design. Topologies are presented and discussed when optimizing linear elastic and thermal properties, as well as for nonlinear properties. The presented method relies on existing SIMP based formulations and sensitivity schemes. MMA is used as the gradient based optimizer and the minimum length scales of the design are controlled through the Heaviside Projection Method.

487 Optimal Topology of Heat-exchanging Fin using Topological Derivative

Akshay Desai, G.K. Ananthasuresh

The topological derivative of a functional quantifies the first-order change in the functional for introducing an infinitesimal hole at a point in the continuous domain. In the paper, the focus is on obtaining the closed-form analytical expression for the topological derivative for a fin and using it to design the optimal topology. We consider a domain wherein we prescribe inward heat flux on some part of the boundary and convection on the remaining part. The objective is to minimize the temperature distribution over the domain for a given volume so that maximum heat convection is possible through the fin.
The domain integral of the performance functional corresponding to the perturbed domain is transformed into a boundary integral on the boundary. It is followed by the asymptotic expansion of temperature due to the introduction of the hole. This calls for the partial differential equation to be solved on the hole boundary. In particular, once we know the behavior explicitly, we evaluate the shape derivative in the form of boundary integral and

perform limit passage on the radius to shrink it to zero. The analytical expression for the topological derivative is derived using this procedure.
The second part of the paper is to obtain topology of the fin for which we evaluate topological derivative at all the points of the domain and remove elements corresponding to the maximum value of topological derivative to minimize the objective function. We will also present the Pareto frontier where we show how the optimum value of the performance functional varies with the volume of material.

488 Automatic Definition of densitiy-driven Topology Optimization with graph-based Design Languages

Manuel Ramsaier, Ralf Stetter, Markus Till, Stephan Rudolph, Axel Schumacher

Today, the product development process is characterized by its diversity. A trend towards customer-tailored products can be observed. This trend demands new processes for product development and manufacturing. Increasing product individuality up to lot size one can be faced by methods, which automate the design process and avoid redundant manual work. As the number of tools involved in the product development process is ever-increasing, one goal is to eliminate the distribution of knowledge into several software tools and begin with one central data model, which is consistent and from where all the used software tools can be automatically triggered. This goal can be addressed by using graph-based design languages, which are based on the Unified Modeling Language (UML). On the manufacturing side one technology for mass-customization can be seen in the additive manufacturing process. For finding the right structure, a combination of additive manufacturing and topology optimization can be advantageous because of the ability of additive manufacturing to create almost arbitrary geometry. On the example of a lightweight multicopter, we propose a graph-based design language which integrates topology optimization and can cover different aspects of the multi-disciplinary product development process: requirements, functions, design equations and costs among others. The topology optimization triggered by the design language can take different product configurations (e.g. battery positioning) into account and accordingly makes several design proposals (i.e. structural proposals for the frame of the multicopter). The executable nature of the graph-based design language reduces the time necessary to design one concept and allows automated design exploration.

489 Stochastic Sensitivity Analysis for Robust Topology Optimization

Xuchun Ren, Xiaodong Zhang

Topology optimization under uncertainty poses extreme difficulty to the already challenging topology optimization problem. This paper presents a new computational method for calculating topological sensitivities of statistical moments of high-dimensional complex systems subject to random inputs. The proposed method, capable of evaluating stochastic sensitivities for large-scale, robust topology optimization (RTO) problems, integrates a polynomial dimensional decomposition (PDD) of multivariate stochastic response functions and deterministic topology derivatives. In addition, the statistical moments and their topology sensitivities are both determined concurrently from a single stochastic analysis. When applied in collaboration with the gradient based optimization algorithm, the proposed method affords the ability of solving industrial-scale RTO design problems. Numerical examples indicate that the new method developed provides computationally efficient solutions.

490 Shape Optimization of Electric Drives based on the Lie Derivative

Erin Kuci, François Henrotte, Christophe Geuzaine, Pierre Duysinx

The optimization of electrical machines is a promising area of concern in industry (from mobile applications to renewable energy conversion), where weight reduction, increase in both torque and efficiency are the major concerns. We tackle these issues through the general setting of a PDE-constrained shape optimization which aims at determining the layout of an existing structure that maximizes the performance measure, under some design constraints which ensure the manufacturability. The shape optimization technique is applied to optimize the design of a classical interior permanent magnet (IPM) machine.

The IPM motor is modeled in terms of the magnetic potential vector A thanks to Ampère's equation, the magnetic Gauss law and a nonlinear constitutive material law. The system is excited by permanent magnets and inductors with a given current density. The shape optimization problem is solved with a mathematical programming algorithm (MMA), where the derivative of each performance measure is established through the Lie derivative.

The general theoretical framework has naturally allowed to overcome the limitations of the classical scalar material derivative commonly used in mechanics, which can only be applied to the scalar magnetostatic system but not for general vector electromagnetic fields. Theoretical formulae to express sensitivity analytically are demonstrated in detail, and applied to the nonlinear magnetostatic problem, following both the direct and the adjoint approaches.

The efficiency of the proposed method is demonstrated on the design optimization of an IPM motor which tends to find the best position of the airgap for a given outer radius to reduce the vibrations due to torque fluctuations. Using the open source finite element code GetDP/Gmsh we obtain the optimal design that allowed to reduce the torque fluctuations by 98%.

491 Development of a bi-gradation semi-active isolation system with leverage-type controllable friction damper

Zhen-Yu Zhan, Tzu Kang Lin

Recent studies have found that a conventional passive isolation system with constant long-period isolation frequency may incur excessive isolator displacement under near-fault earthquakes. To solve this issue, a semi-active isolation system named Leverage-type controllable friction damper (LCFD) is applied. Unlike the traditional variable friction dampers, where the friction resistance force is adjusted by directly controlling the normal force applied on the friction interface, the LCFD system combines a traditional passive friction damper and a leverage mechanism that has a movable central pivot. By controlling the position of the pivot, the equivalent friction force of the LCFD system can be adjusted swiftly. In addition, a bi-gradation velocity control (BGVC) algorithm, which is developed on the basis of hyperbolic function, is applied in the LCFD system to effectively reduce structural response during an earthquake. In order to demonstrate the performance of the proposed BGVC-LCFD system, a series of numerical simulation is conducted by 14 typical earthquakes including seven far-field and seven near-fault earthquakes, respectively. The result has demonstrated that compared to the proportional displacement control (PDC), the excessive displacement of isolation layer induced by a near-fault earthquake can be significantly suppressed the BGVC algorithm, while less control force is used in slight excitations to mitigate the acceleration response effectively.

492 Formulations and applications of transmissible loads in layout optimization

Hongjia Lu, Matthew Gilbert, Andrew Tyas

Although the field of layout optimization has a history stretching back well over a century, the problem of identifying the optimal position of applied loads in addition to the optimal structural layout has received comparatively little attention. This is perhaps surprising, since in many cases the position at which external loads act cannot be precisely determined in advance, and will depend on the chosen structural layout; for example consider the wind loads which act at the external surface of a building.

To solve such problems, so-called transmissible (or ‘design dependent’) loads are sometimes used in layout or topology optimization formulations, with the goal of ensuring that the form of the optimal structure is not influenced by the specific locations of external applied loads. Such loads are usually defined to act along specified lines of action, and have previously been represented in the problem formulation via constrained displacement (rigid bar) or equilibrium (migrating load) formulations. However, it has been observed that these two formulations will provide different solutions for the same set of inputs. In this contribution the range of applicability of each of these formulations is carefully assessed. It is then shown that the constrained displacement formulation should only be used in special circumstances, otherwise misleading structural layouts are likely to be identified.

It is then demonstrated that the constrained displacement formulation can usefully be used in conjunction with discrete layout optimization methods to identify efficient bracing layouts in tall buildings. Considering a 40-storey tall building, it is shown that a simple yet efficient structure can be identified; the latter structure is found to have a 16.9% greater stiffness to material usage ratio than an otherwise identical building with traditional cross bracing.

493 Static and Dynamic Aeroelastic Scaling of the CRM Wing via Multidisciplinary Optimization

Joan Mas Colomer, Nathalie Bartoli, Thierry Lefebvre, Sylvain Dubreuil, Peter Schmollgruber, Joseph Morlier

Novel and disruptive aircraft configurations such as the blended wing-body, the truss-braced wing or the joined-wing aircraft aim to improve the performance of the classical wing-body aircraft. However, there are few to no data of previous similar aircraft to use for the design of these new concepts. For this reason, the use of aeroelastically similar flight demonstrators arises as a means to assess the flight qualities of these new concepts.

Since flight demonstrators cannot often be a scaled down copy in all the aspects (e.g., the internal structure architecture), an optimization approach is needed to find the design that best fits the desired response. In this paper, we present a multidisciplinary optimization approach to design a wing that matches the aerolastic response of the NASA Common Research Model (CRM). This response includes both the static deformed shape, and the scaled flutter modes, speeds and frequencies. In previous works, we successfully tested both the aeroelastic coupling and the dynamic similarity optimization by using test cases on the literature. All multidisciplinary analysis and optimizations were implemented using the NASA OpenMDAO framework. We used a global optimizer with surrogate models and mixture of experts.

For the static aeroelastic part of the problem, we establish a coupling between a panel code and a linear finite element solver by using a Gauss-Seidel iterative method. The optimizer tries to minimize the difference between the nodal displacements of the scaled model and the scaled response of the reference aircraft.

For the dynamic aeroelastic similarity, we first use the traditional approach where aerodynamic similarity is assumed and the problem can be treated as a structural modal optimization. For the optimization, we maximize the sum of the Modal Assurance Criterion (MAC) between the reference and current design modes once they have been paired according to their shape. The MAC value is also used to pair the modes.

494 Status of SMO research in India

Palaniappan Ramu, Ananthasuresh G, Ravi Salagame, vinay Ramanath

SMDO has seen significant growth in methods, practice and tools over the last 3 decades. Yet, adoption of optimization methods, growth in its research and skill development has been lagging in India compared to rest of the world including Asian countries such as Japan, Korea and China. This conclusion is based on limited international published material about work done within India either in academia or in industry. Over the last two decades, there have been a few focused activities through groups such as CASDE at IIT Bombay or adoption of MDO techniques to development of combat aircrafts by government labs. As a growing economy with focus on "make in India" and limited engineering resources, India offers valid opportunity to grow institutional use of optimization methods including MDO across industries. A one-day strategic workshop focusing on current research and challenges was conducted at The Indian Institute of Science, Bangalore. Academic institutions, industrial R&D groups represented by both multi-national companies as well as Indian companies and a few vendors of optimization tools attended the workshop. Overall, the workshop had close to 40 participants including a couple of distinguished leaders from the premier aerospace R&D in India who provided a view of the past activities in optimization in the country. All the inputs were collated, analyzed and aggregated to a few actionable steps both short term and long term. This paper is a document of our findings from the workshop. The need for institutionalized adoption of optimization methods and tools across the industries was unanimously voiced by all the participants. It was also felt that the professional community within the country needs to meet frequently and exchange ideas and best practices. The final paper will talk about setting up a center for excellence in optimization which will be a multi –institute, -discipline and –industry funded center which will seek international collaboration as well.

495 Multimaterial Topology Optimization of Contact Problems using Allen-Cahn Approach

Andrzej Myśliński

The paper is concerned with the structural topology optimization of elastic contact problems. These problems are described by the elliptic variational inequalities. This optimization problem consists in finding such topology of the domain occupied by the body and/or the shape of its boundary that the normal contact stress along the boundary of the body is minimized. In literature this problem usually is considered as two-phase material optimization problem. In recent years multiple phases topology optimization problems have become subject of the growing interest. The use of multiple number of phases during design of engineering structures opens a new opportunities in the design of smart and advanced structures.

The paper deals with the analysis and numerical solution of the topology optimization problem of system governed by the variational inequalities. The domain occupied by the body is assumed to consist from several elastic materials rather than two materials. Material density function is a variable subject to optimization. The regularization of the objective functional by the multiphase volume constrained Ginzburg-Landau energy functional is used. The derivative formula of the cost functional with respect to the material density function is calculated and is employed to formulate a necessary optimality condition for the topology optimization problem. This necessary optimality condition takes the form of the generalized Allen -Cahn equation.. The derivative of the cost functional appears in the right hand side of these equation. Moreover the cost functional derivative is employed to calculate a descent direction in the numerical algorithm. Finite element method is used as the approximation method. Implementation details are introduced. Numerical examples are provided and discussed.

496 Simple Intuitive Multi-objective ParalLElization of Efficient Global Optimization: SIMPLE-EGO

Carla Grobler, Schalk Kok, Nico Wilke

Efficient Global Optimization (EGO) is a response surface optimization method, specifically designed to solve computationally demanding optimization problems. EGO starts with a set of initial designs and iteratively appends one design at a time. EGO uses Kriging to approximate the objective function from the evaluated responses. In addition, EGO relies on the response and uncertainty predictions from Kriging to estimate where the next design should be evaluated. This is achieved by maximizing an acquisition function called Expected Improvement (EI). EI elegantly combines two criteria: i) where the predicted Kriging cost function value is low, and ii) where the Kriging uncertainty is high. These two criteria are referred to as exploitation or exploration respectively.

The classical EGO approach only selects one design to sample in each subsequent iteration. But modern computing hardware has numerous computing cores. This allows multiple simultaneous analyses to be conducted, effectively reducing the time to solution. Therefore this study aims to parallelize EGO, using multi-objective approaches to select multiple designs per iteration.

It so happens that EI has two terms, the first term having an exploitation character, while the second term has exploration character. Therefore Feng et al. proposed treating the two EI terms as the cost functions of a bi-objective optimization problem in the EGO-MO algorithm. However, we propose using the predicted function value, and the uncertainty of the Kriging surface as the two bi-objective cost functions. We find this method more intuitive to understand and simpler to implement. Our proposed method, Simple Intuitive Multi-objective ParalLEl-EGO (SIMPLE-EGO), is justified from the proof that the maximum EI design is Pareto optimal when our two criteria are considered.

The study concludes by comparing the convergence characteristics of EGO, EGO-MO and SIMPLE-EGO on different multi-modal cost functions.

497 A surrogate-based optimization using polynomial response surface in collaboration with population-base Evolutionary Algorith

Shima Rahmani, Masoud Ebrahimi

The evaluation of system design is undaoubtedly a time-consuming process with limited computational budget especially when some criteria such as reliability maximization or cost minimization are introduced as main objectives. This attracts many attentions to utilize the effectiveness of meta-models (surrogate-base methods) in the context of optimization.
In this study, a collaboration betwenn the population of Evolutionary Algorithms (population-based) and a polynomial surrogate model leads to reach local and global optimal points. As populations are formed to search the design space for the best solution, a response surface formation is intended in light of the fitness evaluation of population simultaneously. The accuracy of the response surface then can be increased by making beneficial use of original function evaluation by the population in the next iteration.
To be more precise, construction of the surrogate model occurs in the first iteration through utilizing population cost (using original model) and the updating of this surrogate model is possible by means of the population cost of the next iterations. Meanwhile, the best solution of the surrogate model has to be injected into the population as a new member to empower its search engine. The proposed creativity brings about promising results of global optimal solution with fewer function evaluation.

498 Optimal Orbital Design of a Nadir-pointing Satellite with the purpose of Thermal Load Control

Asad Saghari, Shima Rahmani, Amir-reza Kosari

Orbital parameter assessment as an integral part of a mission design has a parental effect on other subsystems of a satellite. The design and performance requirements of the subsystems are intensely coupled with the orbital parameters. Some parameters such as eclipse time, sun incidence angle with panels, albedo and geothemal radiation depend on satellite orbital parameters. In this study, by doing a dynamic simulation on every aforementioned parameters over the satellite lifetime, the analysis constructed in every moment of the satellite lifespan has been introduced as decision criteria. There are two subsystems of satellite which are mostly under the influence of the orbital characteristics: Electrical Power Subsystem and Thermal Control Subsystem. Moreover. these two subsystems are strongly in interaction with each other so that considering only one of them without the other one is not analytically and practically possible. This paper mainly aims at seeking for an optimal orbit for a nadir-pointing satellite designed based on a specified platform using Evolutionary Algorithms. Mission and Power requirements are considered as constraints to be statisfied as well as controlling the maximum thermal load exerted on the satellite. A computational code has been developed to simulate the performance the satellite mission characterized by high accuracy

499 MDO of a reduced fidelity automotive body-in-white FE model using crushable frame springs and sub space metamodels in trust-regions

Charles Mortished, Jonathan Ollar, Peter Benzie, Royston Jones, Johann Sienz, Vassili Toropov

Reduced fidelity models can be used for concept development in the automotive industry. Recently crushable frame springs [1] have been shown to be suitable for the representation for the crash structure of automotive vehicles [2].

Sub space metamodels are used in multidisciplinary design optimisation (MDO), including disciplines with disparities in design variable dependence. While the MDO problem is still solved in full design variable space, the sub space metamodels are built in reduced design variable space, only taking into account variables relevant to the modelled response. This allows for a reduction in the number of design points needed for each metamodel [3].

In this paper it is shown that when using crushable frame-springs in MDO, sub space metamodels can be used to reduce the number of required characterisations and design point evaluations. By using sub-space metamodels the number of required design points per iteration is reduced, resulting in fewer required low-fidelity design evaluations and crushable frame-springs characterisations. This is demonstrated on an MDO of a low fidelity Body-In-White automotive structure, subject to both NVH and crash load cases.

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500 ParaPy: a Knowledge Based Engineering Framework built on Python

Reinier van Dijk, Bram Timmer

This paper describes the potential of ParaPy, a Knowledge-Based Engineering framework which combines the capture and re-use of engineering knowledge with Computer Aided Design and Computer Aided Engineering capabilities. It has been used to develop parametric, knowledge-based models both for conventional and unconventional product configurations.

The application of the framework discussed in this paper will mainly focus on the aircraft rudder generator that Fokker Aerostructures and ParaPy developed in collaboration.

ParaPy provides a high-level, declarative, Python-based modelling language. This language, and the accompanying Graphical User Interface, have been developed with the focus on ease of application and development effort, as well as re-usability and adaptability of code. This enables rapid development of parametric, rule-based models, even with basic knowledge of Python. Background algorithms conveniently incorporate the key features of a KBE system: dependency tracking, run-time value caching, and lazy evaluation. These features maximize performance and consistency in the generated models, while also enabling them for optimization. Additionally, the platform has been developed with the integration of external analysis tools in mind, making it suitable for setting up Multi-disciplinary Design and Optimizations and also for increased front loading of the design process.

The discussed rudder generator tool has shown that generating geometry and meshes, for structural analysis, can be done in a matter of minutes with a level of detail comparable to that of the preliminary design phase. Additionally, the integration of various analysis programs allowed it to quantify the potential reduction in the time required to design and optimize a product. For example, the time required to structurally design and optimize an aircraft rudder has been reduced from months to weeks. In terms of aerodynamic analysis, other tools show similar results.

501 Grillage layout optimization - theory and numerical methods

Karol Bolbotowski, Linwei He, Matthew Gilbert

This paper describes the development of theory and numerical methods for compliance minimization of a grillage system. The continuous optimization problem is first considered, with the optimum field of beam width distributions sought for a fixed initial grillage geometry. Using variational methods the problem is reduced to a pair of mutually dual, infinite dimensional, linear optimization problems; the primal problem involves minimizing the integral of absolute value of bending moment subject to equilibrium equations whilst the dual problem involves maximizing the virtual work of external loads subject to point-wise curvature constraints.

With the load assumed to be applied at joints only, both optimization problems can be rigorously reduced to finite dimensional, though nonlinear, problems. The two discrete formulations employ two new and nontrivial norms defined on a 2-dimensional vector space. The norms are then proved to be mutually dual which implies that the dualization and discretization processes commute. The well-known theorem which demonstrates the statical determinacy of an optimum truss can be shown to also be applicable to the grillage optimization problem.

The two problems above have been implemented in a computer program and then solved for relatively small-scale grillage problems. Also, to enable larger scale problems to be solved, a linear approximation of the primal problem is proposed which enables application of the 'member adding' technique originally developed for truss layout optimization problems. This allows ground structures with many millions of beams to be treated. This method is then applied to various example problems; it is shown to provide solutions which coincide with the optimum layouts of Michell-type grillages derived analytically by G.I.N. Rozvany and co-workers in the 1970s.

502 Optimization of oriented and parametric cellular structures by the homogenization method

Perle Geoffroy-Donders, Grégoire Allaire, Julien Corital, Olivier Pantz

We present here a topology optimization method based on a homogenization approach to design oriented and parametrized cellular structures. The present work deals with 2-D square cells featuring a rectangular hole, because their structure is close to that of rank-2 sequential laminates, which are optimal for compliance optimization. For several cells, the value and the parametric sensitivities of their effective elastic tensor can easily be computed, by the resolution of a cell problem. The obtained results can be used to build a surrogate model for the homogenized constitutive law. Moreover, we add the local orientation of the cells to our problem. Then, an optimal composite shape is computed thanks to an alternate directions algorithm. The crucial ingredient of the methodology is the extraction of a quasi-periodic and additive manufacturable structure from the previously obtained composite shape, thanks to a space transformation.

503 Robustness criterion for the optimization schemes based on kriging metamodels

Melina Ribaud, Frederic Gillot, Christophette Blanchet-Scaliet, Celine Helbert, Celine Vial

Within the context of robust shape optimization, the computational estimation cost of physical models is usually reduced throughout a metamodel. In the context of computer experiments, metamodels are largely used to represent the output of computers codes. Gaussian process regression (Kriging) is very efficient. Lots of examples of the use of a metamodels can be found in literature. In order to achieve a robust optimization, we introduce the use of the Kriging metamodel with a Matern 5/2 covariance function to predict the moment one of the function and to find the optima. The idea is to optimize with a genetic algorithm like NSGA II the Expected Improvement of the prediction function. However, solutions to optimization problems can be sensitivity to perturbations in the parameters of the problem. The idea of robust optimization is to find an optimum that is the less perturbed as possible by the variation of parameters. In our context, it is impossible to use directly the physical model to approximate the variance. The metamodel that represents the function is used as a replacement of the real function to evaluate the observation points of the variance. Then, the metamodel is employed to predict the function and the variance. Finally, the optimization is achieved with regards to the EI of the function and the EI of the variance. The problem is the superposition of the two metamodels that cumulates prediction errors. Hence, we propose to consider the norm one of the hessian matrix calculated in each point of the conception space as the robustness criterion. This criterion is inspired by the curvature radius that use only the second derivatives on an optimum. The figure shows a function with two optima. The square optimum is the most robust in all direction and has the smallest value of the hessian norm. However, computing derivatives at the same evaluation point are less expensive than adding a new point. Finall, we compare the classical method to ours.

504 Multidisciplinary System Optimisation on the Design of Cost Effective Space Launch Vehicle

Cedric Dupont, Sophie Missonnier, Andrea Tromba

This paper presents the methodology and the optimization strategy for space launch vehicle design, applied by Bertin Technologies for over 10 years and consolidated in HADES software platform.

The formulation of the problem is to find the best concept i.e. the one that maximizes performances (mass on orbit) and minimizes (launch) cost while satisfying mission and architecture constraints. The process includes two levels of optimization to enhance performance and rapidity hence efficiency of the design phase. The strategy is based on a Multidisciplinary Design Feasible (MDF) approach coupled with the use of Genetic Algorithms (GA) for the global optimization and gradient based algorithms for fine ultimate tuning.

The platform provides a software environment integrating a number of technical modules consistently interconnected within a system optimization loop. The platform is flexible and customizable to specific design phases and according needs. The modules may be based on multiphysics models specifically developed for one application, subsystem design models or more general tools such as CFD for aerodynamic calculation and CAD/CAE for mechanical design. The main disciplines integrated in the platform are related to the launchers propulsion, structure, aerodynamics, cost, and obviously trajectory optimization that is the heart of the platform. The use of an integrated platform for multi-objective and multi-disciplinary optimization enables an efficient process and quick optimization maintaining the required precision.

This methodology is particularly well fitted to the design of a small space launch vehicle, allowing to take into account the multidisciplinary nature of such complex system and to manage the inherent sensitivity for this kind of vehicle. The application case presented was used to design Bertin Technologies cost-effective expandable Space Launch Vehicle for microsatellites ROXANE.

505 Topology Optimization for the design of Structural Capacitors: Light-Weighting Unmanned Autonomous Systems

Andrew Gaynor, Raymond Wildman

The Army is constantly striving to light-weight parts and platforms by any means necessary. Traditionally, this is approached through material replacement in legacy parts, but as lightweight materials and structural optimization methods are becoming more prevalent, the light-weighting initiative is plateauing. This necessitates innovative solutions. Additionally, the Army is highly interested in unmanned autonomous systems (UAS), which benefit from light-weighting through improved maneuverability, increased payload and reduced operational energy requirements. With this in mind, a multi-functional approach is taken to

consolidate parts by combining functionality to further light-weight components.
In this work, we develop a new multi-functional topology optimization approach to design structural capacitors. The approach will combine typical structural topology optimization with a new topology optimization scheme to design structural capacitors. First, expanding on previous research community work, the distribution of material in a capacitor with a given conductor geometry (parallel plate, coaxial, etc.) will be optimized assuming the use of two dielectric materials with differing dielectric and mechanical properties. The goal of the optimization is to maximize capacitance and minimize mechanical compliance under a given loading. Second, as a separate optimization problem, conductor geometry will also be optimized assuming a single dielectric material. Finally, trade-off studies are performed to develop the Pareto Bounds for each of these particular design problems.
Ultimately, drastic increases in energy storage on Army UAS platforms is seen through exploitation of multi-functional structural capacitor systems. With designs in hand, manufacturing plans are formulated given current in-house (possibly nScrypt) and industry-wide additive manufacturing capabilities. These help inform future design constraints so that optimized designs are automatically manufacturable.

506 Sensitivity Analysis of Eigenvectors, Response Spectrum Displacements and Stresses

Narayanan Pagaldipti, Shaobin Liu, Xueyong Qu, Raphael Fleury

In certain engineering analysis such as system identification and modal assurance criterion (MAC) calculations, eigenvectors are targeted as design responses. Response Spectrum Analysis is a modal method for approximately calculating maximum displacements and stresses in a structure. Response Spectrum Analysis is widely used for earthquake analysis of buildings and shock loading of ships or submarines. Design optimization of response spectrum displacements and stresses also depend on eigenvector responses. These require robust and efficient calculation of design sensitivities of eigenvectors. Nelsons method is the original method used for eigenvector sensitivity calculations and enhancements to this method have been published.
In this paper, an adjoint formulation for an enhanced eigenvector sensitivity method is presented. A new sensitivity methodology for response spectrum displacements and stresses has also been developed. These formulations are implemented within the commercial software Altair Optistruct for shape, sizing and topology optimization. Several design studies based on this implementation will be presented to validate its robustness, efficiency and practical use.

508 Human-in-the-loop layout and geometry optimization of structures and components

Linwei He, Matthew Gilbert, Tom Johnson, Chris Smith

Numerical truss layout optimization employs a ground structure comprising a large number of structural elements from which the optimal subset is sought. The basic problem formulation can be solved via linear programming, which means that large problems can be solved very quickly. However, although layout optimization has been found to provide a highly effective means of identifying (near-)optimal truss layouts, these can be overly complex in form and hence unsuitable for practical use. Although to address this a range of practical considerations can potentially be incorporated in layout optimization formulations directly (e.g. via inclusion of nonlinear constraints and/or nonsmooth variables), this will normally greatly increase computational cost. Also, some practically important constraints are difficult to specify mathematically (e.g. aesthetic considerations). Furthermore, rather than being presented with a single "optimal" design, designers often seek flexible tools that allow them to interactively modify a design for a variety of reasons.

The present work addresses these issues by using a so-called "human-in-the-loop" optimization framework, in which a designer can step into the design loop to make modifications as required. Initially a standard layout optimization is undertaken, followed by refinement via a geometry optimization step. "Human-in-the-loop" refinement is then undertaken by the designer, who can manually modify the structural layout and/or apply additional design constraints. The modified design can then be checked and, if necessary, optimized further, utilizing geometry optimization. Several practical design problems are presented to demonstrate the efficacy of the interactive design tool developed, ranging from large-scale trusses, for use in building structures, to small-scale small mechanical components, designed to be fabricated via additive manufacturing (3D printing) techniques.

509 Level set topology optimization for design-dependent pressure load problems

Hélio Emmendoerfer Junior, Eduardo Alberto Fancello, Emílio Carlos Nelli Silva

This work presents a level set framework to solve the compliance topology optimization problem considering design-dependent pressure loads. One of the major technical difficulties related to this problem is the adequate association between the moving boundary and the pressure acting on it. This difficulty is easily overcome by the level set method that allows for a clear tracking of the boundary along the optimization process. In the present approach, a reaction-diffusion equation substitutes the classical Hamilton-Jacobi equation to control the level set evolution. This choice has the advantage of allowing the nucleation of holes inside the domain and the elimination of the undesirable level set reinitializations. In addition, the optimization algorithm allows the rupture of loading boundaries, that is, the crossing of the pressured (wet) boundary with the traction free boundary are not avoided. This gives more freedom to the algorithm for topological changes. In order to validate the proposed scheme, several numerical examples are presented.

510 Stress-constrained level set topology optimization for design-dependent pressure load problems

Hélio Emmendoerfer Junior, Emílio Carlos Nelli Silva, Eduardo Alberto Fancello

This work presents a level set framework to solve the topology optimization problem for mass minimization subject to local stress constraints considering design-dependent pressure loads. Two technical difficulties are related to this problem. The first one is the local nature of stresses. To deal with this issue, stress constraints are included to the problem by means

of an augmented Lagrangian scheme. The second is the adequate association between the moving boundary and the pressure acting on it. This difficulty is easily overcome by the level set method that allows for a clear tracking of the boundary along the optimization process. In the present approach, a reaction-diffusion equation substitutes the classical Hamilton-Jacobi equation to control the level set evolution. This choice has the advantage of allowing the nucleation of holes inside the domain and the elimination of the undesirable level set reinitializations. In addition, the optimization algorithm allows the rupture of loading boundaries, that is, the crossing of the pressured (wet) boundary with the traction free boundary are not avoided. This gives more freedom to the algorithm for topological changes. In order to validate the proposed scheme, several numerical examples are presented.

511 Topology optimization of mechanical components fabricated by additive manufacturing for a Shell Eco Marathon vehicle

Pablo Alarcon Soto, Maxime Collet, Simon Bauduin, Eduardo Fernández Sanchez, Antonio Martinez, Pierre Duysinx

Since 2004, a team of students and researchers of University of Liege takes part to the Shell Eco Marathon race with a lightweight electric vehicle. The goal of this pedagogical project is to design, fabricate and operate a vehicle exhibiting the least energy consumption. A key factor to reduce the energy consumption is to minimize the vehicle mass. Besides the body structure made of CRFP, engineers have also to focus on the weight reduction of any mechanical parts of the powertrain, transmission and of rolling gear.

The combination of topology optimization with additive manufacturing techniques allows to propose innovative designs exhibiting a high performance to weight ratio. Topology optimized designs are often characterized by a high geometrical complexity that is not possible to manufacture without 3D printing.

This work presents the CAE design methodology that was developed to combine topology and shape optimization with 3d printing manufacturing. Novel developments both in shape and topology optimization have also been realized for the specific character of these components.

The design methodology is illustrated with several applications of components of our new Eco Marathon prototype. They include a support for electric traction motors and different torque arms of the steering mechanism to be implemented in the new 2017 vehicle.

The presentation is going to show the different design steps from the specifications and the formulation of the design problem to the 3D-printing of the parts: the topology optimization, interpretation and CAD reconstruction, shape optimization and detailed finite element verification of the solution. The optimization is performed thanks to the commercial software NX-TOPOL and the final CAD design is reconstructed in the CATIA environment software after a smoothing procedure in the NX-CAD environment. We show that the final design can be 3D-printed and a comparison with a design produced using traditional design approach is provided.

512 Regularization squeme for controling lenght scale in topology optimization based on bacterial quemotaxis

Jersson Xavier Leon, Juan Felipe Giraldo, Maria Alejandra Guzman

In order to avoid numerical problems in topological optimization such as checkerboards or mesh dependence, different regularization schemes have been used including penalization, continuation and filtering [3]. This research shows a new regularization scheme to avoid these problems in the Bacterial Chemotaxis Based Topology Optimization Algorithm- BCBTOA [1]. This algorithm simulates the behavior of marine bacteria that forms honeycomb patterns to represent the distribution of material in a domain [1], The original algorithm suffered from a faulty tuning of parameters [1] And after making some modifications we have obtained two fundamental parameters that control the algorithm, these parameters are the radius of action of the chemotactic model of communication between bacteria, (parameter R) and the desired volume fraction (parameter f) [2]. When the parameter R changes it restricts the size of the cavities and solid zones in the structure, the solid zones being larger as R increases and retaining the desired volume fraction f. From the above we deduce that the parameter R functions as a regularization parameter to control the size of the structural members. As a result, we obtained several layouts for different topology optimization problems of continuous bi-dimensional structures

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513 Design of Passive Acoustic Wave Shaping Devices and Their Experimental Validation

Rasmus Christansen, Ole Sigmund, Efren Fernandez-Grande

We discuss a topology optimization based approach for designing passive acoustic wave shaping devices and demonstrate its application to; directional sound emission [1], sound focusing and wave splitting. Optimized devices, numerical results and experimental results are presented and benchmarked against other designs proposed in the literature. We focus on design problems where the size of the device is on the order of the wavelength, a problematic region for traditional design methods, such as ray tracing.

The acoustic optimization problem is formulated in the frequency domain and modeled by the Helmholtz equation. An exterior 2D model domain is used and an array of point sources is considered as sound emitters. The optimization goal is to identify a distribution of solid material in a design sub-domain which produce a desired spatial sound field pattern across a frequency band of interest in a target sub-domain. The objective is the integral of the deviation in pressure magnitude, between a prescribed sound field and the solution to the model problem for a given design realization over the target sub-domain. Filtering is used for regularization and to allow for meaningful optimization for geometric robustness [2]. The Globally Convergent Method of Moving Asymptotes is used to perform the optimization [3].

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514 An Improved Aggregation Function for Topology Optimization with Discrete Geometric Elements

Julián Norato, Hesaneh Kazemi

Free-form topology optimization (TO) methods have been widely used to render optimal structures in numerous physical realms. In fabrication processes that consist of joining stock material, however, the organic designs rendered by these methods are difficult to translate into a design that conforms to the manufacturing, resulting in highly suboptimal designs. To alleviate this, the authors and others have recently introduced TO methods to design structures made of discrete geometric elements. Our method consists of smoothly projecting an analytic description of the geometric elements onto a continuous density field on a fictitious domain for simplified primal and sensitivity analyses. Therefore, the design variables are the geometric parameters, while the analysis is performed on a fixed grid, as in existing TO methods. Also, and unique to our approach, we ascribe a size variable to each geometric element that is penalized in the spirit of the solid isotropic material penalization (SIMP) used in density-based TO. This penalization allows the optimizer to altogether remove a discrete geometric element from the design, which makes the optimization more robust and improves convergence.

The geometry projection at a point in the fictitious domain and for a single geometric element renders an effective density. Since several geometric elements can overlap at a point, in previous work we aggregated the corresponding densities into a composite density using a p-norm. While this approach is effective, the nonlinearity of the p-norm hampers the optimization and requires the use of a small move limit. In this work, we consider a different aggregation strategy, whereby the effective densities corresponding to different geometric elements are aggregated via a Heaviside-based filter. We demonstrate this strategy with numerical examples, and show through these examples that it produces improved convergence, in the order of that of existing density-based TO methods.

515 Multi-fidelity extension to non-intrusive Proper Orthogonal Decomposition models and dedicated surrogate based optimization methodology

Tariq Benamara, Piotr Breitkopf, Ingrid Lepot, Caroline Sainvitu

The design of complex engineering systems relies more and more on Multi-Disciplinary Optimization. Surrogate based optimization methodologies have been considered for the past decades as potential solution to alleviate the computational burden of modern optimization campaigns. Nevertheless the usage of high-fidelity simulations within Surrogate Based Optimization loops, can be unaffordable, especially for high-dimensional problems. Multi-fidelity surrogate modeling can be a good way to improve the quality of surrogates while maintaining the training computational cost within acceptable limits. We propose in this contribution to integrate a recent multi-fidelity extension to non-intrusive proper orthogonal decomposition based surrogate models within a Surrogate Based Optimization framework. This multi-fidelity extension to non-intrusive proper orthogonal decomposition is obtained by re-interpreting the concept of constrained proper orthogonal decomposition in order to interpolate precise, albeit costly high-fidelity simulations and approximate abondant, yet less accurate lower-fidelity data. The proposed surrogate models are associated with dedicated infill criteria able to choose both the interesting locations to compute to enrich the training database, and the level of fidelity each new sample should be computed with in order to maximize the predictability over computational cost ratio. The proposed methodology is evaluated on both analytical optimization problems and one industrial optimization of a 1.5 stage booster.

516 Classical Problem Formulations of Compliance Minimizing and Maximizing of Discrete and Discretized Structures - Material Laws at the Optimum Revisited

Wolfgang Achtziger

We study classical SAND problem formulations minimizing or maximizing compliance of discrete or discretized mechanical structures subject to elastic equilibrium and a linear ressource constraint. Besides displacements the problems possess one control variable per finite resp. per structural element, as usual. We investigate formulations where the element stiffness matrices either depend linearly or depend inverse-linearly on these variables. The considered problem formulations play important roles in the field of classical optimal topology design as well as in calculations of best/worst case scenarios of structural degradation measured in terms of compliance. By means of potential energy and by standard operations of convex analysis the considered problem formulations are analyzed in view of their hidden material behavior at optimal contral variables. As is well known, for truss structures there are close relations to problem formulations optimizing complementary energy. Furthermore, it turns out that the problems based on the linear and on the inverse-linear model, respectively, are related through a convexification concept in terms of element-wise strain energy. Analogous relations hold if complementary energy is considered for trusses. Some of these results were derived years ago in join works with J.E. Taylor and M.P. Bendsoe. Summarizing, some of these relations are well known while some others have not been investigated closely in the literature. The intention of the talk is to present a systematic overview on all problem formulations. Moreover, we present some mathematical relations of the element-wise energy functions linking different problem formulations with each other on an element level. Some of these results may be interpreted as the discription of possible stiffness change per element within an optimization scenario based on compliance or on complementary energy with respect to a given structural ressource bound.

517 Average-worst-case topology optimization using stochastic programming and Conditional Value-at-Risk

Geoffrey Oxberry, Cosmin Petra, Mark Stowell, Andrew Barker, Dan White, Dan Tortorelli

Additive manufacturing has enlarged dramatically the design space in engineering applications by enabling designers to manufacture parts of almost any shape. Deterministic formulations of topology optimization problems assume a fixed number of possible boundary conditions (e.g., load cases in solid mechanics), constant/homogeneous material properties, and no geometric variability. However, these three assumptions are violated in practical experience, and could affect substantially design performance. Stochastic topology optimization formulations attempt to compensate for these violated assumptions.

Traditional approaches to formulating stochastic topology optimization problems tend to use linear combinations of the mean and variance (or standard deviation) of a design figure of merit (e.g.,compliance) with respect to a given probability density. However, this choice of mean-variance objective (or constraint) tends to underweight worst-case events in non-normal probability distributions.

Borrowing an approach for modeling financial risk, we propose replacing mean-variance expressions with the conditional value-at-risk (CVaR), where the x-CVaR of a random variable is its expected value over the worst x% of cases – the average-worst-case". We present a CVaR-based stochastic programming formulation for compliance minimization, and compare its performance with mean-variance formulations. Using results from these case studies and from the stochastic programming literature, we argue the case that CVaR better compensates for worst-case tail events by showing differences in the CVaR of the design figure of merit compared to the CVaR of this figure of merit computed using mean-variance formulations.

518 3D structural topology optimization of wind turbine blades with stiffness and frequency constraints

Christian Carstensen, Mathias Stolpe, Susana Rojas Labanda, José Pedro Blasques

This work presents results for the 3d, multi-material, structural topology optimization of large wind turbine blades with stiffness and frequency constraints. Modern wind turbine blades are essentially very large and slender, high performance, thin-walled beam structures. The structure of the blade is made of laminated composite materials and represents only about 5-7% of the total volume enclosed by the outer aerodynamic shape, i.e., blades have low solidity. Total thickness of the panels composing the blade is in the order of 1 cm. In order to achieve representative feature sizes using standard 3d structural topology optimization techniques would require about 1 billion solid finite elements to mesh the entire blade volume. The solution of such a problem is perhaps possible but is definitely impractical. This problem is circumvented here by instead optimizing the structural topology at a series of 2d sections along the length of the blade. A 3d filtering technique is presented which ensures longitudinal continuity. The 3d topology of the blade is finally recreated based on the 2d cross section solutions. This is achieved through a type of homogenization step at each of the sections to determine the stiffness and mass properties which are then mapped onto a beam finite element model for the evaluation of the displacement, and frequency constraints. It has been previously shown that the accuracy of these approach is comparable to shell and solid finite element models albeit using only a fraction of the computation time. Results are presented for the simultaneous material and topology optimization of wind turbine blades for minimum mass with tip displacement, static moment, and frequency placement constraints. The analysis tools and problem formulations are standard within many modern wind turbine blade design optimization framework thus rendering the proposed approach directly applicable in an industrial setting.

519 On the numerical approximation of Michell trusses and the improved ground structure method

Tomasz Sokół

The theory of Michell structures plays an important role in structural topology optimization, by enabling derivation of exact analytical solutions for least-weight structures capable of transmitting the applied loads to the given supports within limits of permissible stresses in tension and compression. Analytical solutions for given boundary conditions are, however, very hard to obtain because require a proper prediction of the optimal layout, also a proper division of the design space onto appropriate sub-regions. Fortunately, this most important and difficult prediction phase of the optimal layout can be performed numerically using ground structure methods. The main advantage of these methods results from the fact that the topology optimization problem can be formulated as a linear programming problem (i.e. convex and free of local minima), thus enabling to find the globally optimal solution. Nevertheless, a dense set of nodes with a huge number of possible connections, i.e. potential bars, is required to obtain a good approximation of Michell truss.

The paper deals with a new method of solving large-scale optimization problems related to Michell trusses. The method is an extension of the adaptive ground structure methods developed recently by the author. In the present version both bars and nodes are switched between active and inactive states in subsequent iterations. Moreover, the displacement field in empty regions is now updated in a more advanced way then before allowing significant reduction of the size of the problem. To properly update the sets of active bars and active nodes in subsequent ground structures, the sensitivity analysis of both primal and dual variables are taken into account. The method was verified in a number of benchmark tests confirming its efficiency, but what is more significant it also facilitated obtaining the new important exact solutions of Michell trusses.

520 Robust Sensor Network Design under Sensor Malfunction for In-Situ Temperature Estimation of Li-ion Battery Pack

Taejin Kim, Sunuwe Kim, Byeng D. Youn

Thermal management is one of the important functions for the battery management system (BMS). In this study, as a part of the thermal management system the in-situ temperature monitoring method is developed by combining the battery thermal model and the locally measured temperatures. The overall procedure is composed of two schemes; the development of the battery pack thermal model and the robust sensor network design. The battery pack is modeled using the lumped parameter model in which a node represents a single cell. The thermal properties of the cell are found by the thermal characteristics tests [1, 2]. Then the thermal maps emulating various conditions of the battery pack are generated from the model, and used to extract the data-driven basis vectors of the system [3]. The data-driven basis vectors enhance the accuracy of the estimation by confining the temperature distribution domain to more probable region defined by the training data set. With these basis vectors, an arbitrary system behavior could be approximated by estimating the corresponding amplitudes. The accuracy of the estimated amplitude, hence the reconstruction of the system behavior, depends on the measurement locations. In this study, the sensor network is designed considering not only the estimation accuracy but also the robustness, because, in spite of the importance of sensing in BMS and the possibility that the broken sensor could collapse the whole monitoring system, the research on sensor malfunction has not been widely studied. Hence, the robust sensor network that the estimation performance does not sharply fall down with the broken sensor is developed. The optimization problem to find the sensor locations that satisfy both the estimation performance and the robustness is formulated, and the solution is found by the genetic algorithm. Finally, the proposed study is validated for various operating conditions.

525 Geometric design of tumbling mill lifter bars utilizing the discrete element method

Daniel N. Wilke, Nicolin Govender, Raj K. Rajamani, Patrick Pizette

The energy consumption of bulk materials handling consumes around 10% of the annual energy utilization on the planet, often driven by inefficient processes. A primary process in the reduction of particle size to fine grind are ball mills. Ball mills utilize ball charge to aid the grinding and are usually used as a primary grinding solution. Ball mills usually operate with charge around 30% with ball mill units utilizing up to 20MW while standing up to a height of around 9m. Industrial ball mills draw around 0.0011% of the world's total power. We consider the geometric design optimization of the lifter bars for a ball mill. By utilizing the discrete element method (DEM) the collision frequency, relative velocity between colliding particles and contact force to estimate the specific impact energy for the ball mill is available. In this study we investigate the effect of the geometry of the lifter bar, that is height and bar angle with respect to the side wall, has on the specific impact energy for various charge distributions. In addition to the specific impact energy the energy spectra of the ball mill is computed to assess the energy distribution in normal and shear interactions. As the discrete element method is computationally demanding we investigate the extent to which the computational cost can be mitigated by following a multi-fidelity approach in which the number of particles and particle sizes are scaled to reduce the initial computational cost and only refined as the design optimization converges. Towards this aim we consider a virtual problem in which we aim to design the lifter of a tumbling mill for a specified power draw of the mill. The problem under consideration is denoted virtual as the solution of the problem is known a priori. This allows us to quantify and assess the quality of the obtained designs using the various strategies. The associated computational cost when considering the full computational model against the multi scaled computational m

526 Topology Optimization for Additive Manufacturing Considering Penalty for Overhang Support

Fabian Fuerle, Ming Zhou, Raphael Fleury

In the past decade topology optimization has seen rapid and broad acceptance across all major industries. It has been shown that it can help create surprisingly efficient design in engineering fields where products are already considered highly sophisticated. For example, applying topology optimization Airbus achieved over 40% weight reduction on a group of A380 leading edge ribs. Successes have been demonstrated across most industries where structures play an important role in product design and development. As topology optimization often creates free-forming 'bionic' structures, interpretation of design concept that fits traditional manufacturing methods has been a challenge. On the other hand, additive manufacturing, 3D-Printing in popular terminology, offers almost unlimited freedom for design shape and form. Because of this exciting symbiosis topology optimization has gained increasing recognition from the very broad 3D-Printing community. In recent years research papers on topology optimization specifically targeting 3D-Printing have increased significantly. Several papers proposed approaches for topology of support free structures satisfying a given overhang angle. This paper will approach this manufacturing aspect from a slightly different angle. In essence printing support is a pure cost factor as it adds material usage, printing time and cost for post treatment. On the other hand, a structure satisfying a strict overhang angle could potentially significantly sacrifice structural performance. Therefore, it is more appropriate to address printing support as additional cost where the amount of support in the design can be controlled by the cost as a part of the objective function.

527 Continuum Shape Sensitivity Analysis for Fluid-Structure Interaction using an Arbitrary Lagrangian-Eulerian Reference Frame

David Sandler, Robert Canfield

Continuum Sensitivity Analysis (CSA) is a computational method to calculate the sensitivity of aeroelastic response with respect to changes in vehicle shape. CSA differentiates the nonlinear governing fluid-structure interaction (FSI) partial differential system of equations to arrive at a linear system of partial differential continuum sensitivity equations (CSEs). We first differentiate the FSI boundary conditions to specify the sensitivity boundary conditions. Then, the CSEs may be discretized and solved. Whereas boundary conditions must be differentiated using the material (total) derivative, it is advantageous to derive the CSEs using local (partial) derivatives. We ensure accuracy of this CSA boundary velocity formulation through spatial gradient reconstructions (SGR) to overcome inaccuracy compared to domain velocity or discrete analytic formulations. The benefit is that geometric sensitivity, known as design velocity, is not required in the domain. In contrast to the usual discrete sensitivity approach, a principal advantage of CSA is that mesh sensitivity is avoided altogether. Thus, knowledge of the workings of a automatic mesh generator is unnecessary and the mesh Jacobian matrix never calculated. An important feature is distinguishing design velocity from grid velocity at the FSI interface for arbitrary Lagrangian-Eulerian (ALE) reference frames, which are often needed for aeroelastic gust response involving rigid body motion. This CSA method with SGR is developed in a nonintrusive manner for gust response, enabling use with common FSI analysis tools. The CSA method is applied to an example problem of the transient gust response of a two-dimensional airfoil attached to a body mass by translational and rotational springs. An in-house finite element code for potential flow, as well as a commercial Navier-Stokes solver are used as black-boxes for the flow analysis

531 Bayesian Identification

Hermann G. Matthies

Many mathematical resp. computational models of natural phenomena contain parameters constants or even functions which have to be identified and calibrated for the model to be accurate. These parameters in a way represent specific knowledge resp. information about the phenomenon in question. The calibration or identification process can be seen as adding new information to the model.

Introducing new information into a probabilistic description of knowledge is typically performed via some kind of application of Bayess by now classical theorem. To avoid ambiguities (which did arise historically), the mathematically precise description of conditional probabilities in Bayess theorem, especially when conditioning on events of vanishing probability, is formulated via conditional expectations, and is due to Kolmogorov.

Nevertheless, most sampling approaches to Bayesian updating typically start from the classical formulation involving conditional measures and densities. These are usually the distributions of some random variables describing the prior knowledge. Here an alternative track is taken, in that the notion of conditional expectation is also taken computationally as the prime object. Being able to numerically approximate conditional expectations, one has a complete description of the posterior probability.

A further task is to construct a new transformed, or filtered random variable which has a distribution as required by the (posterior) conditional expectations. In the talk, the abstract task and its solution will be presented first, and then different computational approximations will be sketched, as well as different ways of stochastic discretisations, adding another level of approximation.

532 Bead optimization with a Genetic Algorithm for reducing mechanical stresses in weldseams

Sierk Fiebig

More and more optimization methods, especially the topology optimization, are implemented and used inside the development process of mechanical components. The development of casting parts profits mostly from this trend. The results of a topology optimization are easy to interpret as casting parts. With the integration of casting process simulations, low weights and good manufacturing abilities are possible. For sheets parts, the topology optimization must be extended with special manufacturing constraints and integrated deep drawing simulations. Therefore the bead optimization, as special shape optimization method, is interesting. By modifying the design of the sheet, for example in a trapezoid shape, the stiffness and eigenfrequencies of the part can be increased. Additionally mechanical stress values can be minimized. Because of the normally decreased maximum acceptable mechanical stress values in weldseams in comparison to the base material, stress reduction in the area around the weldseams is the preferred objective function for the bead optimization. This contribution presents a combination of improved bead pattern in combination with a Genetic Algorithm. The bead pattern allows bead structures in a uniform distance in the 2D-orientation of the sheet to increase the symmetry of new bead designs. The Genetic Algorithm focuses the design space and similarities inside the space to increase the effectivity of the optimization. Individuals with a very similar coding will be removed from the population. The higher diversity increases the result quality and minimizes the needed simulation time.

533 Robustness optimization within the development process by integration of manufacturing tolerances in the simulation

Clément Hayer, Sierk Fiebig, Thomas Vietor, Jürgen Sellschopp

In an increasingly challenging environment of growing competition and stricter legal regulations, the concept of lightweight design gets more and more important for the automotive industry. Usually, the goals of lightweight tend to conflict with the robustness of the designs. The scattering of the geometry within the manufacturing tolerance leads to a divergence between the test bench results and the prediction from simulation. For an optimized lightweight design, this deviation will often lead to a violation of the requirements. In this case, the part has to be re-designed to improve its robustness, causing an additional time expense, higher costs and a higher weight.

This paper presents a new way to answer the conflict of objectives between lightweight and robustness. By the integration of manufacturing tolerances in an early stage of the product design, the robustness of a part can be improved without increasing its weight. A parametric CAE model is used to represent all deviations of the geometry and material properties within the tolerance range. Additionally, an analytic expression of the relevant simulation results is built. These tools are not only used to predict exactly the scattering of the test bench result, but also allow optimizing the tolerance ranges in order to obtain a 100% satisfaction of the requirements in every tolerated configuration.

The optimized tolerance ranges make it possible transferring the weight advantage generated in the structural optimization into the design of prototypes. Through a better prediction of the test bench results in the simulation, unnecessary development loops can be avoided. The presented procedure is the first one that integrates manufacturing tolerances within the simulation with the objective of optimizing the tolerance ranges beyond a simple parameter optimization. Thereby, new weight potentials are allowed, and the development process can be substantially shortened.

534 Modified Ideal Gas Molecular Movement Algorithm based on Quantum Behavior

Mohammad Reza Ghasemi, Hesam Varaee

Recently, the ideal gas molecular movement (IGMM) algorithm was proposed by the authors as a new metaheuristic optimization technique for solving single and multi objective optimization problems. Ideal gas molecules scatter throughout the confined environment quickly. This is embedded in the high speed of molecules, collisions between them and with the surrounding barriers. In IGMM algorithm, the initial population of gas molecules is randomly generated and the governing equations related to the velocity of gas molecules and collisions between those are utilized to accomplish the optimal solutions. In this paper a new IGMM algorithm is proposed based on quantum behavior of molecules. Quantum based IGMM (QIGMM) is intended for enhancing the ability of the local search and increasing the individual diversity in the population. QIGMM improve capability of IGMM in avoiding the premature convergence and eventually finding the function optimum. startlingly, all these are obtained without introducing additional operators to the basic IGMM algorithm. The effectiveness of these improvements is tested by some standard benchmark and engineering optimization problems. experimental results show that, QIGMM algorithm is more effective and efficient than the original IGMM and other approaches.

535 An integrated framework of risk assessment for spent nuclear fuel storage facility under aircraft crash

Sanghoon Lee, Belal Almomani, Dongchan Jang, Hyun Gook Kang

An overview of a risk evaluation framework for an aircraft crash into an interim spent fuel storage facility using a probabilistic safety assessment is presented. Damage evaluation of a detailed generic cask model in a simplified building structure under aircraft impact is discussed through a numerical structural analysis and an analytical fragility assessment. Sequences of the impact scenario are shown in a developed event tree, with uncertainties considered in the impact analysis and failure probabilities calculated. Risks are estimated for three specification levels of cask and storage facility structures to evaluate the influence of parameters relevant to design safety. The proposed assessment procedure includes the determination of loading parameters and reference impact scenario, structural response analyses of facility walls, cask containment, and fuel assemblies, and a radiological consequence analysis with dose-risk estimation. The risk results for the proposed scenario in this study are expected to be small relative to design basis accidents for best-estimated, conservative values. The importance of this framework is seen in the flexibility to evaluate facility capability to withstand aircraft impact and the expectation of potential realistic risks; the framework also provides insight into epistemic uncertainty in the available data, and into the sensitivity of design parameters for future research. The work is one part of a bigger research to build an integrated framework of PSA for spent nuclear fuel storage facility and it can be further utilized to optimize the design, operation and regulatory framework for spent fuel storage considering the risk and economic aspects.

536 A Two-Phase Approach based on Serial Approximation for Reliability-Based Design Optimization

Ming Zhou, Zhifan Luo, Ping Yi, Gengdong Cheng

The original problem of reliability-based design optimization (RBDO) is a nested two-level problem that is computationally time consuming for real engineering problems. In order to overcome the computational difficulties, many formulations have been proposed in the literature. These include SORA (sequential optimization and reliability assessment) that decouples the nested problems. SLA (single loop approach) further improves efficiency in that reliability analysis becomes an integrated part of the optimization problem. However, even SLA method can become computationally high expensive for real engineering problems involving many reliability constraints. This paper presents an enhanced version of SLA where the first phase is based on approximation at nominal design point. After convergence of first iterative phase is reached the process transitions to a second phase where approximation of reliability constraints are carried out at their respective MPP points. Examples show that the proposed approach consumes much less finite element analyses while achieving equal solution quality.

537 Cost and weight optimization of hybrid parts using a multi-material topology optimization approach

Paul Falkenberg, Eiko Türck, Thomas Vietor

Topology optimization is widely used in the industry with the objective to minimize the weight of structures or to maximize their stiffness. Typically, there is no special focus on the costs of the resulting part, as there is a direct correlation between material costs and weight.

When looking at hybrid designs, combining a lightweight material with high costs and a material with lower costs but worse specific properties, this simplified view on costs is no longer sufficient. The correlation between costs and weight of the part is no longer met, as the material costs highly depend on which material is primarily used. The optimization problem, therefore, extends to a multi-objective problem with the competing aims minimization of weight and reduction of costs. Additionally, a more complex manufacturing process has a major share in the overall costs of the part.

The presented approach uses an extended cost calculation model to estimate the manufacturing costs of the hybrid component based on its geometrical properties. The epsilon-constraint-method is used to transform the costs objective function into an additional constraint. To be able to satisfy this new cost constraint, a group of fuzzy rules, which influence the usage of each material and therefore the costs, were added to the step size controller used by the topology optimization approach. By varying the costs constraint, different Pareto-optimal solutions can be found.

538 An approach to use the structural intensity for acoustical topology optimization

Sebastian Rothe, Sabine Langer

The aim of vibroacoustic engineering is to find a part design which is optimal in strength, weight and acoustics. Topology optimization is an universal tool to find an optimal construction shape in early design stages. Based on numerically calculated local mechanical values, the optimizer used in this contribution decides to delete or add material in the region concerned, based on one value, e.g. stress. The aim is to find the best possible utilization of the material's mechanical strength, regarding the component weight. This approach works very well for static problems.

However, in acoustics, a dynamic system has to be solved. It is important to take the mechanical behavior of the surrounding areas of the focused region into account. In addition, a frequency dependency exists. All mechanical information have to be determined and - if possible - reduced to a single mean value, comparable to vonMises stress, to make a decision on structural changes. A reliable value to assess local areas of a construction, regarding the relevance for the overall acoustical behavior, is still missing.

The idea of this paper is to use the structural intensity (STI) as a value for assessment. It combines two essential mechanical properties: the stress-tensor and the acoustically important velocity-vector. The STI represents the structure-borne sound energy ow and its direction at each point. These information could be used to lead the optimization algorithm to build up a component topology with improved acoustical properties. The approach presented shows how the structural intensity could be used to assess each voxel concerning its acoustical impact.

540 Topographical Optimization for Surface Properties of Materials

Qing Li, Hongyi Ren, Ali Entezari

The wettability is one of the important surface properties of materials, which is typically characterized by static contact angle (CA). The factors influencing the wettability are mainly the chemical composition and microstructure of the surface of the material. This paper first describes the theoretical basis of solid surface wettability, including surface tension, surface free energy, the wetting process and several theoretical models such as Young model, Wenzel model and Cassie-Baxter model. In this study, two types of pillars with square and triangular shapes are selected, respectively, to form the unit-cell of surface topographies. Based on theoretical models, the relationship between equilibrium CA and critical topographical parameters (e.g. size of pillars and pitch between pillars) is determined. The numerical simulation of dynamic two-phase flow is then conducted using the volume of fluid (VOF) method in computational fluid dynamics (CFD). Through the numerical solutions, the deformation process of droplet impact is simulated, revealing that the contact angle depends on topography in terms of shape and size parameters of unit cells. Finally, the design optimization is performed to seek minimum, maximum and desired contact angles, respectively. The surrogate modeling techniques are used to relate the CA to design parameters for different topographies. The results show that the optimized topography enables to generate a desired wettability of surface.

541 XFEM Based Topology Optimization of Ceramic Structures for Enhancing Fracture Resistance

Zhongpu Zhang, Shiwei Zhou, Miachael Swain, Grant Steven, Qing Li

Peak tensile stresses usually indicate the likelihood of fracture and fatigue failures in ceramic structures, such as dental prostheses. Thus minimization of peak stresses signifies a major goal in design of all-ceramic systems, typically comprised of porcelain and zirconia. This study aims to develop a new procedural basis for design of mechanical-sound all-ceramic structures based upon Bidirectional Evolutionary Structural Optimization (BESO) and eXtended Finite Element Method (XFEM), in which both minimization of peak tensile stress to strength ratio and associated fracture incidence criterion are taken into account. A series of demonstrative examples are presented for porcelain-zirconia materials with or without pre-cracks. The results show that this newly proposed XFEM based non-gradient topology optimization method is able to improve the structural design by minimizing fracture incidence. This BESO procedure provides a new tool to develop optimal ceramic structures, being of particular implications to design of prosthetic devices in biomedical engineering.

542 SIMP-ALL: a generalized SIMP method based on topological and shape derivatives

Alex Ferrer, Samuel Amstutz, Charles Dapogny

The popular SIMP method addresses the topology optimization problem by filtering techniques leading to a relaxation on the characteristic function. In this sense, the constitutive tensor is then determined by an empirical interpolation law [4]. In this work [3], we present a novel interpolation law that matches the continuous gradient of the cost functional with the topological derivative [2] on the 'black and white' region. Additionally, the continuous gradient tends to the shape derivative [1] on the 'grey region' (interface) as the filtering vanishes. Two different features account for the reasons of referring to the presented method as SIMP-ALL. Conceptually, on the one side, the approach sheds light on connecting the SIMP method with the shape and topological derivatives. On the other side, our numerical investigations suggest that the interpolation law satisfies the H-S bounds. In contrast with the SIMP method, this feature results in a physical interpretation of the grey elements regardless the material properties of the domain. On top of that, the presented approach permits the use of continuous optimization methods. Some numerical examples computed with the level-set and projected gradient algorithms illustrate the SIMP-ALL method. Additionally, we present the SIMP and SIMP-ALL interpolation laws for different material properties in relation with the H-S bounds.

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543 Optimization of Bistable Shallow-thin Shells without Pre-stress

Safvan Palathingal, G. K. Ananthasuresh

Bistability of an elastic structure implies that the structure can be in two stable equilibrium states in the absence of external forces. Bistable shells exist in engineered devices and the natural world. Many of them rely on pre-stress for their bistable behaviour. In this work, we consider shallow-thin shells that can be bistable without pre-stress. A shallow shell is one whose height is much smaller than its planform. A thin shell is one whose thickness is much smaller than its height.

We show that there is scope for optimization of shallow-thin shells in view of switching and switch-back forces as well as the distance travelled by points of interest between the two states. Optimization variables include shape of the shell, thickness-profile, and support conditions. In this work, we vary the shape of the shell for chosen thickness-profile and support conditions.

Three approaches are followed to pose and solve the optimization problem for maximizing the travel with constraints on switching and switch-back forces. The first approach entails numerical optimization wherein the shape of the shell is a linear combination of basis functions that are chosen based on only the support conditions. The optimization variables are the weights in the linear combination, which is often less than five. In this approach, sensitivity analysis is challenging because analytical expressions for gradients are not easily tractable.

The second approach is semi-analytical wherein the deformation of the shell is also expressed as a linear combination of the basis functions used for defining the shape of the shell. This approach follows the methods developed for shallow arches and is amenable to obtain approximate gradients. Furthermore, it helps to gain insights into the extent of optimality and to get appropriate initial guesses for numerical optimization followed in the first approach. The third approach uses the known method of optimal arches and combines arches to create a shell.

544 Optimization of Width-Profiles of Bistable Arches

Niharika Gupta, Safvan Palathingal, G.K. Ananthasuresh

Unlike a straight beam, a slender arch is known to exhibit bistability because it can have two stable equilibrium states in the absence of external forces. Such an arch is known as a bistable arch. Some of the important characteristics of these arches are switching force, travel, stability, etc. Bistable arches with various arch profiles in their as-fabricated shape, each with different boundary conditions, have different force displacement characteristics. Most of the previous work discussed the importance of boundary conditions and arch-profile keeping the cross-section uniform except a few which considered the effect of depth of the arch.

In this work, we show that width-profile too plays a significant role in determining the characteristics of a bistable arch. Thus, we optimize the width-profile for a given arch-profile and boundary conditions to minimize the switching force. Constraints are imposed on volume of material and upper and lower limits on the width. Optimization is performed using the optimality criteria method in the framework of calculus of variations and semi-analytical method for finding the nonlinear force displacement characteristic of bistable arches.
Substantial reduction in the switching force is seen in the optimized width-profile of pinned-pinned arches, as compared to uniform width-profiles. An interesting observation is that bistability is also seen in the portion left out from the uniform-width profile after subtracting the optimized profile; indeed, it performs better than the optimized width-profile in terms of switching force, travel, stability, etc. Thus, two conjugate bistable arches are obtained by optimally partitioning a given arch of uniform width-profile. Hence, optimization helps improve the performance of a bistable arch and also helps in material and manufacturing economy in terms of conjugate designs. A semi-analytical method, optimization, and validation through prototypes are described in this work.

545 Design Exploration based upon Internal Structure of Materially Nonlinear Response Sensitivities

Jan Liedmann, Franz-Joseph Barthold

The definition of a structural optimisation problem is based on experience and knowledge of the designing engineer. Decisions, tackling the kind of design parametrisation, type and number of design variables, as well as relations between design variables mainly affect the quality of optimisation results and the computational effort. These decisions can be facilitated by means of structural design exploration based upon response sensitivity information, cf. [1]. The internal structure of response sensitivites, i.e. eigen- and singular values and vectors, as well as corresponding spectra of pseudo load and sensitivity matrices, is examined by means of singular value decomposition (SVD). Hence, provision of pseudo laod and sensitivity matrices is essential for this purpose. Considering material nonlinearities, additional sensitivity information of internal variables, representing the deformation history, have to be provided, cf. [2].

A numerically effective way of computing response sensitivities, including pseudo load and sensitivity matrices, is the variational approach, that is deriving analytical gradients utilising variational principles, cf. [3]. This approach is based on an enhanced kinematic concept that offers a rigorous separation of geometry and physics. Additionally, it allows simultaneous determination of structural response and response sensitivities within a finite element framework. Sensitivities and subsequent discretisation can be derived easily, see [4].

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546 Towards improved local optima with SCP based optimization algorithm

Michael Stingl, Lukas Pflug

We discuss a class of material optimization algorithms based on the sequential convex programming idea. In contrast to the standard approach implemented, e.g., in the well known MMA algorithm, in each major iteration a separable model is established on the basis of the parametrized material, which can be - depending on the application - a material tensor parametrized by rotation angles, a physical density computed using a power law or any other smoothly parametrized material property.

The potentially nonlinear and non-convex parametrization is then treated on the level of the sub-problem, for which, due to separability properties of the model, globally optimal solutions can be computed. It is shown that an appropriately globalized variant of the algorithm converges to a first order critical point and is at the same time able to escape from poor local solutions. In order to achieve the latter, we use the fact that - when applied to cost functionals which are linear in the state variable - in theory the separable model can be chosen to resemble the approximated function exactly along each coordinate axis. Although such a choice turns out to be prohibitive in practice, this observation can be exploited to generate under- and over-estimators. These are used to drive the algorithm towards improved local optima, which are characterized by the fact that they can not be improved by coordinate-wise changes the design.

The relevance of these theoretical observations is demonstrated by computational studies ranging from Truss Topology Design to parametrized Material Optimization of continuum structures.

547 A shifted-constraint RBDO framework using Monte Carlo Simulations

Shima Rahmani, Asad Saghari, Masoud Ebrahimi

In this paper, a sampling-based framework for reliability-based design optimization (RBDO) problems has been developed to provide a comprehensive structure adaptable to MCS methods such as importance sampling strategy. This framework has the capability of adopting any reliability analysis by decoupling two integral parts of a RBDO algorithm: reliability analysis and optimization problem. A shifting vector strategy has been proposed what imposes the constraints to immediately satisfy the reliability requirements. The main advantage of this framework is its independency on the approximation of the constraints since it aims at finding an optimum shifting vector based on the probability density function of the constraints themselves. Numerical examples are illustrated to compare the proposed algorithm with other well-known RBDO methods to show the efficiency.

548 Woven Lattice Materials with Tunable Stiffness, Permeability and optimised material architectures - Smart Structures and Materials

Manuel Pelacci, Jao Aguero, Yu Liu, Stefan Szyniszewski

Our objective was to explore fluidic properties of the architected woven lattice materials. Recently a new class of woven lattice materials was introduced. Manufacturing consists of weaving of metallic filaments and is followed by metallurgical brazing to produce stiff, yet lightweight sheets. The weave construction can be described in a DNA-like notation such that selected filament inserts can be inserted or skipped to create a wide range of mechanical, fluidic and thermal properties. We have performed wind tunnel studies of permeability at a range of Reynolds numbers also to capture the effects of turbulence for over a dozen 3D printed architectures. The results were compared with a random metallic foam fluidic characteristics. Since 3D woven architectures are orthotropic in nature, directional variations in the flow properties were observed. Also, the optimum designs may be achieved if one enlarges the unit cell extend such that it contains a number of weft and warp insertions. Future work is needed to incorporate turbulent effects in the computational predictions adequately. More importantly, broader work is needed on the development of discrete optimisation tools to identify material architectures with desired thermal, fluidic, structural and crashworthiness characteristics.

550 Blend Repair Shape Optimization for Damaged Compressor Blisks

Ricarda Berger, Jan Häfele, Benedikt Hofmeister, Raimund Rolfes

During service life of an aircraft engine, the highly loaded compressor blades are subjected to wear and may get damaged. In order to prevent further critical damage, the blades are refurbished and partial defects are removed by blending repairs. While the blending of the blade only leads to small modifications in the shape, it still impacts the structural properties. Even a small variation of the geometry may cause a significant change in the modal properties of the structure. Thus, it has to be analysed how blend repairs affect the vibrations of the refurbished blade and how the repair processes can be enhanced. In the presented work, the optimal shape of blend repairs is determined considering the vibration behaviour of the blade. The costs of a repair measures result from the quantity of material removed and the subsequent deviation in natural frequencies. The location, form and orientation of the repair is specified through a parameterized description. For this purpose, a modified Particle Swarm Optimization algorithm is applied. Studies are carried out aiming at establishing an efficient optimization procedure for the blend repair of integrated compressor structures. The study assesses and presents in particular the influence of the blend repair parameters on the decisive natural frequencies related to material removal.

551 Multi-disciplinary Optimization of Body Exterior Structures

Michel H.J.W. Paas, Hessel C. van Dijk

Multi-disciplinary Design Optimization (MDO) uses optimization methods to solve design problems by incorporating all relevant disciplines simultaneously. The Objective is to opti-

mize the weight of the body exterior (including) closures while maintaining attribute performance. Attribute performance is assessed by involving various load cases from crash safety, NVH, durability & strength, forming and vehicle dynamics. MDO has been incorporated in Fords Global Product Development System. Multiple optimization loops are conducted during the development process.
Closed loop optimization involving multiple large-scale FE models in conjunction with many design and response variables is infeasible. Therefore, the MDO Process is based on optimization of so-called meta-models, which act as real-time substitutes of numerically intensive CAE models. Furthermore, meta-models provide detailed system knowledge, hence they can be used for additional parameter and robustness studies. The MDO process comprises following steps: 1) Data generation involving creation, submission and post-processing of various DoEs, 2) Meta-modeling and Optimization, and 3) Validation of optimization proposals.
Meta-modeling is based on Gaussian Processes, which capture the uncertainty in predictions resulting from both the intrinsic noise in the problem and the errors in the parameter estimation procedure. Furthermore, they are immune to over-fitting, can be used to fit arbitrarily complex relationships, and can take advantage of inherent structure in the data. In Gaussian Processes with Automatic Relevance Determination individual length scale parameters are introduced for each input dimension in the covariance function. For large length scales the associated inputs can be discarded, thus enabling dimensionality reduction and improved predictive quality.
The viability of different enhancements will be demonstrated with findings in recent MDO projects.

553 Topology Optimization Applied to the Design of a Blood Pump

Emilio Silva, Juan Romero

The main function of a blood pump is to have a suitable hydraulic performance while maintaining good haematological compatibility which consists of avoiding hemolysis (release of hemoglobin from red blood cells) and thrombosis (clotting). However, the challenge of improving the performance of these blood pumps requires the solution of an inverse-based design optimization problem, in which an oriented search must be conducted to obtain the optimized design. The rotor is a main component in the blood pump and the design of rotor topology can play an important role in the pump performance and its haematological conditions. Thus, performance improvement of these devices can be achieved by using topology optimization techniques. Thus, in this work, topology optimization techniques are applied for designing the rotor pump such that the energy dissipation, and power consumption (related to pump hydraulic performance) and vorticity (related to haematological conditions) are minimized. A two-dimensional finite element derived for a rotating frame is applied to model the rotor flow behavior. The modeling predicts the flow field between relative two blades of a rotor without considering the influence of the volute. A modified Cross model is adopted for the non-Newtonian fluid modeling. It is assumed that the blood is flowing an idealized porous medium subjected to a friction force, which is proportional to the fluid velocity and the inverse local permeability. A porous flow model is considered with a continuous permeability design variable for each element that defines the local permeability of the medium and allows the transition between fluid and solid property. The design optimization problem is solved by using the method of moving asymptotes (MMA). Numerical examples are presented to illustrate this methodology. Finally, it is verified that an improvement of the hemolysis index can be achieved by minimizing the vorticity in the rotor.

554 Modular Design Concept Generation for a Collection of Interacting Systems with Application to Modular Vehicle Fleet Design

Alparslan Emrah Bayrak, Arianne X. Collopy, Bogdan I. Epureanu, Panos Y. Papalambros

A collection of interacting systems, such as a fleet of military vehicles, can have a life-cycle benefit from sharing interoperable modules. Defining the modules that maximize such benefits must be addressed at the early stages of system design. We present a multi-objective optimization framework for conceptual modular design. We use a functional representation of the supersystem, i.e., the interacting systems collection, to make module design decisions informed by supersystem requirements and life-cycle objectives. The resultant modules are configured into a variety of architectures and form a set of systems with distinct capabilities that meet supersystem requirements. We apply this approach on a fleet of military vehicles. Computational results quantify the intuition that designing a large number of smaller modules reduces overall fleet weight and increases required personnel resouces because of larger demand for vehicle reconfiguration.

555 Optimization of an Automobile Torque Arm Using Successive Response Surfaces

Erdem Acar, Nahide Tüten, Mehmet Ali Güler

In automotive industry, design for lightweight automobile structures has become a well established practice. Design optimization of an automobile torque arm subjected cyclic loading is performed in this paper. The shape of the torque arm is optimized to minimize the weight of the torque arm such that the fatigue life of the torque arm and the maximum von Mises stress at the torque arm are constrained. The stresses and the fatigue life are computed using ANSYS Workbench finite element software. Response surfaces are utilized to reduce the computational cost of optimization. Two different response surface based optimization approaches are used: (a) optimization using global response surfaces, and (b) optimization using successive response surfaces. It is found that the weight of the torque arm can be reduced by about 26% using global response surfaces, and the weight of the torque arm can be reduced by about 29% using successive response surfaces.

556 A robust level-set topology optimization method for mechanical metamaterials

Zhen Luo, Jinglai Wu, Hao Li

This study will develop a robust topology optimization method using level sets for design of mechanical metamaterials with interval-random variables, e.g. the material Young's modulus is assumed as a random variable and the material Poisson's ratio is regarded as an interval variable. The objective function of the robust design is defined by interval mean and interval

variance of the deterministic objective function, while the interval mean and interval variance are estimated via a Polynomial Chaos-Chebyshev Interval method for the hybrid uncertain analysis. Then the sensitivities of the robust design objective function can be achieved, based on the information of the uncertain analysis. After that, a level set method in parametric form is used to find the topological shape of the microstructure, associated with the numerical homogenization method. The proposed method is actually non-intrusive and general, and can be easily extended to the broad family of metamaterial design problems.

557 Development of a Computational Model for Topology Optimization of an Aircraft Wing

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Topology Optimization (TO) is a technique that allows the identification of the optimal material distribution in response to given boundary conditions applied to the design volume. The design freedom it allows, together with the development of innovative manufacturing techniques and advances in material science, makes it a promising tool for the aerospace sector. The chance to explore new structural wing layout as alternatives to the traditional spars-ribs-covers configuration, motivates the authors to perform TO subject to manufacturing constraints, expressed in the form of non-design regions and volume fraction thresholds. The optimization is carried out using Altair OptiStruct, software based on the SIMP method. The design volume is here defined by the Common Research Model (CRM) wing box. The volume is represented by the plain material wing box, fully clamped at the root section, to which are assigned the Aluminum properties. The objective of the optimization is the compliance minimization, while the lower and upper limits of the volume fraction are treated as constraints. For the first simulation the aerodynamic load is applied as a uniform distribution of forces over the entire upper surface of the wing box. No fuel or engine loads are introduced since the fuel distribution is not known a priori. Preliminary results corresponding to the described settings show an internal layout characterized by two thick skins and a spar-like element. Such a structure is expected to withstand the shear stress and the bending moment. The absence of transversal elements (ribs) clearly depends on the fact that the aerodynamic loads are not applied locally at equally spaced stations along the wing span, as in other published works. This main difference suggests that an innovative layout can be obtained by enforcing general boundary conditions. Further development of this model will take into account more accurate load configurations as well as the manufacturing constraints.

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